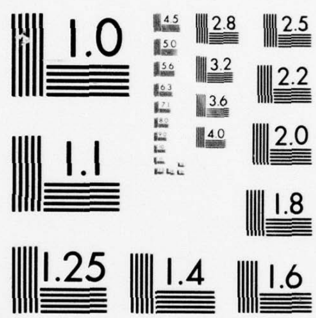
AD-A053 476 AIR FORCE HUMAN RESOURCES LAB BROOKS AFB TEX F/G 6/16
RECORDING PILOT EYE MOVEMENT BEHAVIOR: APPROACHES AND POSSIBLE --ETC(U)
DEC 76 W B ALBERY
UNCLASSIFIED AFHRL-TR-76-81 NL

1 OF 1
AD
A053476

END
DATE
FILMED
6 -78
DDC



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

AFHRL-TR-76-81

AIR FORCE HUMAN RESOURCES LABORATORY

AD A053476

AD No.
DDC FILE COPY

2

RECORDING PILOT EYE MOVEMENT BEHAVIOR: APPROACHS AND POSSIBLE APPLICATIONS

By

William B. Albery

ADVANCED SYSTEMS DIVISION
Wright-Patterson Air Force Base, Ohio 45433

December 1976
Final Report for Period 1 July 1975 – 30 August 1976

Approved for public release; distribution unlimited.

DDC
RECEIVED
MAY 3 1978
E

AIR FORCE SYSTEMS COMMAND
BROOKS AIR FORCE BASE, TEXAS 78235

NOTICE

When US Government drawings, specifications, or other data are used for any purpose other than a definitely related Government procurement operation, the Government thereby incurs no responsibility nor any obligation whatsoever, and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data is not to be regarded by implication or otherwise, as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

This final report was submitted by Advanced Systems Division, Air Force Human Resources Laboratory, Wright-Patterson Air Force Base, Ohio 45433, under project 6114, with HQ Air Force Human Resources Laboratory (AFSC), Brooks Air Force Base, Texas 78235. Mr. William B. Albery, Simulation Techniques Branch, was the principal investigator.

This report has been reviewed and cleared for open publication and/or public release by the appropriate Office of Information (OI) in accordance with AFR 190-17 and DoDD 5230.9. There is no objection to unlimited distribution of this report to the public at large, or by DDC to the National Technical Information Service (NTIS).

This technical report has been reviewed and is approved for publication.

GORDON A. ECKSTRAND, Director
Advanced Systems Division

DAN D. FULGHAM, Colonel, USAF
Commander

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: 14 AFHRL-TR-76-81

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle): 6 RECORDING PILOT EYE MOVEMENT BEHAVIOR: APPROACHES AND POSSIBLE APPLICATIONS.

5. TYPE OF REPORT & PERIOD COVERED: 9 Final rept. 1 July [redacted]75 – 30 Aug[redacted]976,

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s): 10 William B. Albery

8. CONTRACT OR GRANT NUMBER(s)

9. PERFORMING ORGANIZATION NAME AND ADDRESS:
Advanced Systems Division
Air Force Human Resources Laboratory
Wright-Patterson Air Force Base, Ohio 45433

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS:
62703F
61140706

11. CONTROLLING OFFICE NAME AND ADDRESS:
HQ Air Force Human Resources Laboratory (AFSC)
Brooks Air Force Base, Texas 78235

12. REPORT DATE: 11 Decem[redacted]976

13. NUMBER OF PAGES: 44 12 44p.

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office): 16 6114 17 07

15. SECURITY CLASS. (of this report): Unclassified

15a. DECLASSIFICATION DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

(Editor Note: Title for AFHRL-TR-76-81 was changed after TRACE was published. Request TRACE holders revise the title [TRACE not distributed to DDC]).

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Advanced Simulator for Pilot Training (ASPT)
computer image generation
corneal reflection devices
eye mechanism models
fiber optics
field of view
Honeywell Oculometer
Kalman filter
Oculography
pilot workload
recording eye movements

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

An in-house effort was conducted to investigate the physiology of the human visual control system, to review previous models and develop new models for the system using data from advanced bio-medical instruments, to investigate the applications of these instruments to the flight training environment, and to suggest avenues of research opened by the development of advanced eye movement recorders. Types of eye movements and eye movement systems were researched along with methods of recording. Using frequency response data from an oculometer and a corneal reflection eye movement recording device, a control system model of the eye servo system was developed. The design of a non-restrictive eye movement recording device, the Honeywell oculometer, is discussed and a method of integrating the instrument with an Air Force flight simulator, the Advanced Simulator for

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

404 415 JOB

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE(*When Data Entered*)

Item 20 Continued:

Pilot Training (ASPT), is presented. The applications of the oculometer for training fledgling pilots, verifying the necessary visual simulation field of view, and controlling areas of visual display content by point-of-regard are presented. A method for correlating eye scan behavior with pilot workload is presented.

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE(*When Data Entered*)

SUMMARY

Problem

Several investigators have suggested that one method of understanding a pilot's workload, or his performance, would be to record his eye movements while flying. The problem is there is no extensive data base of pilot eye scanning behavior. Most of the available data is of a general form and from light aircraft; virtually none exists for jet aircraft. One reason for this data gap is that an eye movement recording system has never been developed for a jet aircraft which records both the pilot's immediate field of view (FOV) and his fixation point.

Approach

The approach taken was to (a) search the literature for past eye recording techniques and eye movement studies, (b) choose an eye movement monitoring system, (c) check out the system in the laboratory, and (d) analyze the recordings. No formal funding or support was given for this effort.

Results

A literature search uncovered many interesting techniques for recording eye movements. The method selected was the corneal reflection technique. Several manufacturers make corneal reflection eye movement cameras; the device chosen for the study was lightweight and relatively inexpensive. The instrument exhibited accuracy of fixation of better than 1° over a $\pm 20^\circ$ horizontal and $\pm 10^\circ$ vertical range. The device was used to measure a human's tracking performance and a plot and model were made from the data. Using a linear regression analysis technique, the data were correlated with pilot workload and a method for optimally scanning was developed.

Conclusions

A search of the literature for potential eye movement recording systems resulted in the selection of the corneal reflection technique. Through the use of fiber optics, the camera can now be isolated from the lens and a lightweight, helmet-mounted eye movement recording system appear feasible. The NAC eye movement recorder, used in this study, appears to be a relatively inexpensive answer to recording a jet pilot's eye movement behaviors in the aircraft. The recording and application of these eye movements in a flying training simulator reveal some very interesting research issues.

ACCESSION for

NTIS White Section ☑

DDC Buff Section ☐

UNANNOUNCED ☐

JUSTIFICATION ....

....

BY ....

DISTRIBUTION/AVAILABILITY CODES

Dist. AVAIL. and/or SPECIAL

A

PREFACE

This study was initiated by the Advanced Systems Division, Air Force Human Resources Laboratory (AFHRL), Wright-Patterson AFB, Ohio, under project 6114, Simulation Techniques for Air Force Training, Mr. Don R. Gum, Project Scientist, and task 611407, Modeling and Computation. The research was performed at the Advanced Systems Division, AFHRL, with Mr. William B. Albery as principal investigator. The effort was conducted during the period from 1 July 1975 through 30 July 1976.

The author wishes to achknowledge the guidance and support of Dr. Leo Lipetz, Department of Biophysics and The Ohio State University, Dr. Richard M. Campbell, thesis advisor, The Ohio State University; Dr. John Hornseth, Aerospace Medical Research Laboratory, who provided the eye recorder which was used in this study; and Ms. Cheryl Gilliland who typed the draft report.

This report was developed as a thesis for partial fulfillment of the Master of Science Degree in Biomedical Engineering at The Ohio State University, August 1976.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

List of Illustrations (*Continued*)

LIST OF TABLES

RECORDING PILOT EYE MOVEMENT BEHAVIOR: APPROACHES AND POSSIBLE APPLICATIONS

I. INTRODUCTION

The study of eye movements was undertaken by Advanced Systems Division, Air Force Human Resources Laboratory, Wright-Patterson Air Force Base, Ohio, with a specific area of application. This application was aircraft simulation for pilot training. The national energy crisis has necessitated the increased use of flying training simulators throughout the military and commercial communities. The Air Force is particularly interested in developing methods to improve the performance of undergraduate pilots, while reducing the costs of training.

In an effort to enhance this training, a study was initiated to examine and explore pilot eye movement behavior. The intent of this study was to determine if an experienced pilot's eye scan pattern could be used to train an inexperienced pilot on how to scan his visual movements more efficiently.

There were three stated objectives:

1. The primary objective was to examine pilot eye movement behavior and develop eye movement applications to pilot training.

2. The second objective was to evaluate the recorded pilots' eye scan patterns and determine if there is a correlation between pilot scanning behavior and pilot performance.

3. The third objective was to examine the premise that an experienced pilots' eye movements could be used to train a novice pilot and obtain better scanning performance.

This report examines only the primary objective, and offers suggestions for accomplishing the second and third objectives.

II. APPROACH

The approach to accomplishing the primary objective of this study included a review of the physiology of the eye, a review of the literature on past eye scan studies of auto drivers and pilots, and the selection of an eye movement recorder (EMR) for use in the effort. After the selection of an EMR, the approach was one of becoming familiar with using the system. Since the Air Force primary jet trainer, the T-37B, is also the vehicle simulated in the AFHRL Advanced Simulator for Pilot Training (ASPT), a training research device, it was anticipated that the results of this study could be investigated in the T-37B, as well as the ASPT. This topic is dicussed in Appendix E. An approach for achieving the long-range objectives was also considered and is discussed.

A review of the anatomy of the eye (Appendix A) provided the investigator a background on the physiology involved. This gave the expected range of eye movements as 45° left or right, 40° up and 60° down, and 30° in extorsion or intorsion (Young, Zuber, & Stark, 1966). It was also determined that the study would have to consider at least two of the seven known kinds of eye movements, the saccadic (occurring in pulses of 120 to 250 msec at a velocity of 600°/sec) and pursuit movements (occurring continuously at velocities of 1 to 30°/sec) (Young, 1963).

A study was made of methods of recording eye movements. The intent was to base the use of an eye recording device on (a) the range and response performance of the human eye, and (b) the applicability of using such a device in a jet aircraft.

The literature search on oculography, which is the recording and measuring of eye movements, uncovered some very interesting techniques, which date to 1870. These methods are discussed in detail in Appendix B. Of primary interest were those techniques which did not require the pilot to place any foreign materials on his eye and which included an immediate reference to what the pilot was looking at while his scanning pattern was being recorded. Only two eye movement recorders were identified which could satisfy these requirements. One technique was the corneal reflection eye movement recorder and the other was the oculometer, which is an infrared eye scanning instrument.

Because of the convenience, and low cost (compared to the oculometer), a corneal reflection/eye movement camera was chosen for the purposes of this study.

The investigator discovered that the Aerospace Medical Research Laboratory at Wright-Patterson AFB, Ohio owned a very lightweight, corneal reflection type eye movement device. The NAC (manufacturer's name) was obtained and evaluated. Using the NAC EMR, the investigator examined the performance of the instrument with respect to range, resolution, and accuracy in a laboratory environment.

Several studies on pilots' eye movements in both aircraft and simulators have been conducted (Mackworth & Mackworth, 1958; Thomas, 1963; Tiffin & Bromer, 1943). Tiffin and Bromer (1943), concluded from their studies that there were no clear-cut differences between the eye movement patterns of experienced and inexperienced pilots. They recorded the pilot's eye movements directly using a motion picture camera mounted in the cockpit. It is very doubtful whether a researcher could accurately correlate eye movements measured by such a system with what the pilot was actually attending to; as a result, Tiffin and Bromer's (1943) results are suspect. As discussed later (Mourant & Rockwell, 1971), other researchers found that there was a difference between novice and experienced automobile drivers' eye scan patterns. As discussed in the next section, the NAC system used in this study is capable of coincidentally recording both the pilot's fixation point and the immediate field of view (FOV) in front of him.

Work Performed and Results

The actual work performed in this study included a review of eye recording techniques, obtaining the NAC EMR, and using it in studies at Wright-Patterson AFB.

A description of the NAC EMR (including pictures) is given in Appendix C; the main features of the system are that it is lightweight (less than one pound on the pilot's helmet), and that it superimposes the pilot's fixation point (which appears as a white V on the film or video tape) over a primary image of a 60° FOV scene directly forward of the pilot's momentary head position. Since it is lightweight and head mounted, it allows the pilot to perform his normal head movements. Another of the NAC's advantages is that it gives the researcher not only a continuous record of eye movements but also head position information. Some of the disadvantages of the instrument are that it (a) is restrictive, in the sense that the pilot wears the recorder as he would a pair of glasses or goggles, (b) is FOV limited (23° and 31° vertical and horizontal, respectively, for the 30° NAC and 44° and 60° vertically and horizontally, respectively, for the 60° NAC), and (c) requires constant calibration because it can and does slip on the wearer's head. Nevertheless, the NAC appeared to be the most suitable instrument available for accomplishing the primary objective of this study.

In an effort to satisfy the main objective of this study, which was to develop an eye movement measuring system, the NAC was used at Wright-Patterson AFB by the investigator to (a) record subjects' eye movements, (b) determine the performance characteristics of the NAC, and (c) compare the performance of the NAC with data from another instrument, the oculometer. The details of these results are discussed in Appendix D; however, the highlights of the results are as follows:

1. The NAC demonstrated an accuracy of less than 1° error over a range of eye movements of ±20° horizontal and ±10° vertical with the head held fixed.

The eye movement range of ±20° horizontal and ±10° vertical was selected as a characteristic range of expected eye movements about a central axis of vision. A T-37B pilot has approximately a 300° horizontal

and 180° vertical FOV in which he can move his head freely. An accuracy of 1° was chosen for several reasons. It was decided that in order to resolve which instrument or which landmark the pilot was looking at, a 1/2 inch accuracy was required for fixations on the instrument panel and 10 foot accuracy at 500 foot altitude was necessary. The instrument heads on the T-37B instrument panel are 2- and 3-inch diameter, in general, but they are as close as 1/2 inch apart. Also, small lights and other panel hardware are 1/2 inch or less in diameter. As a result, this meant that for an eye-to-instrument panel distance of over 22 inches that a 1/2-inch error would be accurate to within 1.27°. A goal of 1° was set for the accuracy of the instrument.

2. The instrument was quite capable of recording both saccadic and pursuit eye movements, the types of eye movements identified with pilot scanning behavior.

Using the grid chart as a reference, the subject was asked to fixate alternately on all four corners as quickly as he could. The eye-mark could be observed traversing the chart as quickly as the pilot could move his eyes, sometimes a total of 40° in a fraction of a second. Slow, pursuit-type movements were very easily tracked by the recorder. Blinks merely blanked out the eye-mark over the period of the closure.

3. The human eye tracking system has very low bandwidth, with both amplitude and phase performance dropping off at frequencies above 1Hz for a subject tracking a ±10° horizontal sinusoidally moving target.

A sinusoid was tracked using the NAC at seven different frequencies: 0.75 Hz, 1.00 Hz, 1.25 Hz, 1.50 Hz, 2.00 Hz, and 2.25 Hz. The purpose of this experiment was to familiarize the investigator with the system and gathering data. The subject tracked the ±3 cm sinusoid from a distance of 17 cm, so that that his eyes were tracking ±10° from his nominal viewpoint. The data (Table 1) were hand-scored from the TV monitor; these data were gathered at Wright-Patterson AFB.

Table 1. **NAC Data**

Frequency (Hz)	Amplitude[a]	Phase (degrees)[b]	Comments
0.75	17cm/17cm=1.00	0°	smooth, accurate
1.00	1.00	0°	smoooth, accurate
1.25	1.00	lag	slight lag
1.50	0.925	lead	leading input
1.75	0.77	lead	leading input
2.00	0.54	?	no tracking
2.25	0.31	?	subject gave up

[a]The value for the amplitude was derived by measuring the total amplitude of the recorded signal and then measuring the amplitude of the excursion the eye was able to make in tracking the signal. These measurements were made from a TV monitor. As the frequency increased, the subject's ability to maintain fixation contact with the input sinusoid diminished.

[b]Phase information was estimated as it was most difficult to measure the exact location of the eye-mark during each cycle of the input signal. Each frame of the video tape would have had to have been evaluated and measured to obtain a good estimate of the phase.

4. The eye movement performance data recorded using the NAC at Wright-Patterson AFB compared favorably with similar data taken from an oculometer at Aerospace Medical Research Laboratories (AMRL) (Appendix D).

The plots (Figure 1) summarize the data contained in Appendix D.

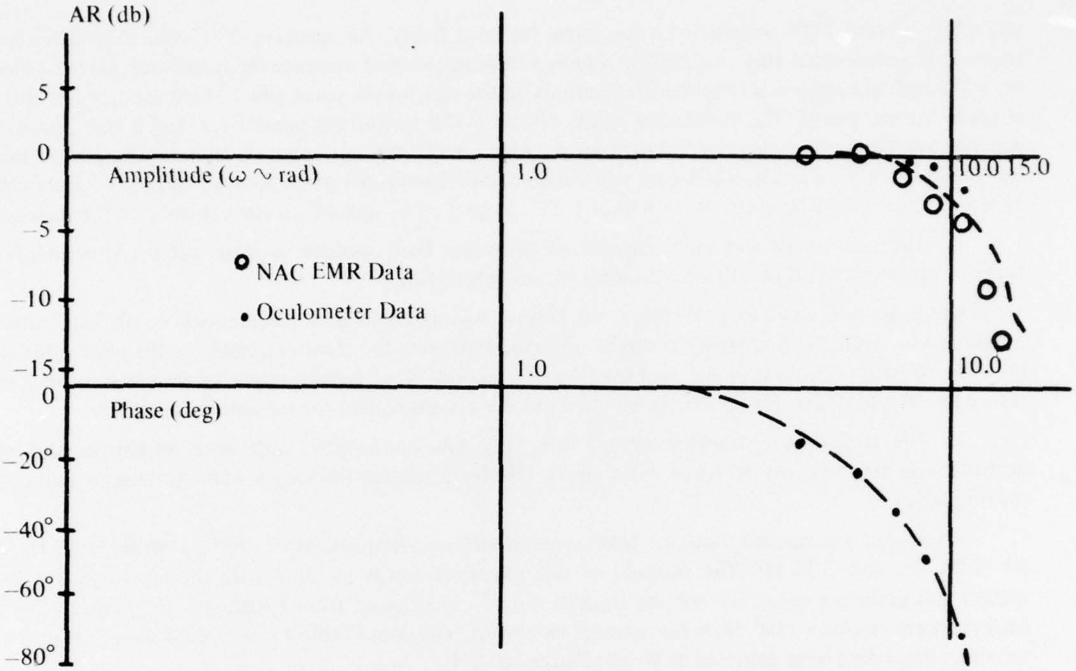


Figure 1. **NAC EMR and oculometer performance data.**

5. A transfer function model of the eye pursuit tracking control system generated by the investigator from this data compared favorably with other models based on data obtained with the oculometer system.

A transfer function model was developed from the NAC data and was compared to similar data obtained from the oculometer. See Appendix D for more details. After plotting both amplitude and phase characteristics of the NAC and oculometer data, it was found that a transfer function for the phase data did not fit the amplitude data. As a result, two separate transfer functions were developed for the data:

$\theta_o(s)$ = output eye position

$\theta_i(s)$ = input signal

Amplitude ratio data transfer function:

$$\frac{\theta_o(s)}{\theta_i(s)} \cong \frac{1}{s^2/11^2 + 2(.6)s/11 + 1}$$

Phase angle data transfer function:

$$\frac{\theta_o(s)}{\theta_i(s)} \cong \frac{1}{s^2/15^2 + 2(.4)s/15 + 1}$$

These results reaffirmed that a linear model for the eye servo system will not compare well with the experimental data.

Analysis of the Results – Discussion

In reviewing the primary objective of this study the following observations are made:

The NAC EMR appears to be a feasible means for recording a pilot's eye movements in jet aircraft. Although the investigator knew before the start of the study that the two major problems with the data would be scoring and calibration, the corneal reflection eye-mark system appeared to be the best instrument available to meet the objective. The NAC system can be used to gather useful information about the visual cues the pilot uses both inside and outside the cockpit.

The calibration problem with the NAC results from two types of errors (a) pilot's eye irregularity error, and (b) helmet slippage error. The first type of error results from the non-spherical shape of the pilot's eye. Some pilots' eye movements cannot be recorded using the NAC.

The purpose of developing an eye measuring system in a T-37 is to gain information about pilot eye scan patterns. Although the long-range objectives of this study were not investigated, an approach to accomplishing each objective was formulated.

An attempt at correlating an experienced pilot's eye movements with his performance has not been made to date, because of other higher priority efforts; however, a scheme for such a correlation is presented.

It would appear to the investigator that the interim step in achieving a correlation between eye scan pattern and performance would be to first investigate a correlation between pilot eye scan and pilot workload;[1] that is, to first correlate those parameters measured by the eye recorder to pilot workload measured in terms of the standard Cooper-Harper ratings.[2]

6. By predicting a pilot's workload, subjective pilot rating could then be replaced with an objective measure of workload. If the pilot rating, or workload, could be correlated with performance, then there would be a direct relationship between pilot scanning data and pilot performance. The development of such a workload measure is as follows:

The first attempt at developing a workload model would be done with a simple task, such as an instrument landing system (ILS) spproach in a simulator, such as the Advanced Simulator for Pilot Training (ASPT). This study would not be complicated with the addition of out-the-window visual cues. Out-the-window visual cues could be a second study if a correlation between eye scan data and workload were established in the simpler-to-analyze ILS case. The NAC recordings on video tape could be studied for the ILS case and the parameters for percent of time spent on the ILS system, probability of transition from the ILS to horizontal situation indicator (HSI), mean dwell time on each instrument, and so forth could be tabulated. A possible experimental set-up and computed parameters could be as stated in Figure 2.

Using a stepwise regression analysis (Waller, 1976) to develop the data into a model of workload, the inputs would include most of the measurements of scan behavior in the previous table. A total of about 150 parameters plus their squares would enter as independent variables. These parameters would include time on instruments, transition rate, average dwell time on each instrument, and so on.

The dependent variable in such an analysis would be workload in the form of the Cooper-Harper pilot rating given by an instructor pilot to the two conditions. A separate set of measurements of each parameter would result from each simulated approach made.

The function of the program would be to select from among the independent variables in the input a set which would best describe (or predict) the pilot rating. The result of such a model would be of the form

[1] Workload is defined as the amount of physical and mental activity the pilot exerts while flying a particular task.

[2] These subjective ratings range from 1 to 10 and relate to the aircraft handling qualities under varying atmospheric conditions.

Simulator Test Conditions

Initial Condistions
X = 33,000 ft.
Altitude = 1,600 ft.
Airspeed = 150 knots

Condition I: No turbulence; pilot rating = 3.0
Condition II: Maximum turbulence; pilot rating = 5.0

Average of Selected Parameters Recorded from NAC EMR Video Tapes
(Hypothetical Data)

Parameter	Condition I	Condition II
Time on instruments, %	95	90
Not tracking, %	3	4
Instrument Transition Rate, sec^{-1}	.7	.5
ILS transition rate, sec^{-1}	2	4
Time on each instrument, %		
Airspeed Indicator (AI)	7	1
ILS	80	85
Altimeter	3	1
HSI (Hor. Sit. Ind)	1	3
VSI (Vert. Sit. Ind)	4	2
Average dwell time on each instrument, sec		
AI	.6	.2
ILS	2.8	4.6
Alt.	.3	.3
HSI	.2	.2
VSI	.4	.2

Figure 2. **Hypothetical Results.**

$$y_i = a_o + \sum_j a_j x_{ij}$$

where y_i is the pilot rating for run i, x_{ij} are the corresponding measurements for the jth NAC EMR parameter in the model, and a_o is a constant. An example of how one would analyze these measurements is as follows (Waller, 1976):

1. *Cooper-Harper rating.* For example, if six test conditions (e.g., turbulence, 500 foot offset from glide slope, etc.) were evaluated, the pilots could assign values from 1 to 10 to these conditions. The response variable Y is the pilot's Cooper-Harper rating of the condition.

2. *Record and analyze eye movements.* The video tape of the pilot's eye movements during the six conditions would be replayed and analyzed frame by frame. Mean dwell times, transition times from instrument to instrument, etc. would tabulated. The parameters which would enter the regression equation would be: (a) a constant representing a rating bias, (b) total time spent on the instruments, (c) number of transitions from the ILS to the HSI, (d) number of transitions from the glide slope indicator to the roll information from the ILS, and (e) number of transitions within the ILS.

3. *Set up of the equation.* Following the analysis presented in Waller, 1976 an equation of the form follows:

$$Y = 5.771 - (1.384 \times 10^{-7})\ (\text{total time on instruments})^2 + 229.2\ (\text{ILS, HSI}) + \ldots + 509.6\ (\text{mean dwell time, ILS})$$

This equation (Figure 3) can be plotted for the six conditions; a theoretical result would look like this for each of the six conditions and the standard deviations. It is anticipated that this type of analysis would result in a relatively low probable error. Such an error would be considered low when compared with the amount of variation commonly experienced in subjective ratings.

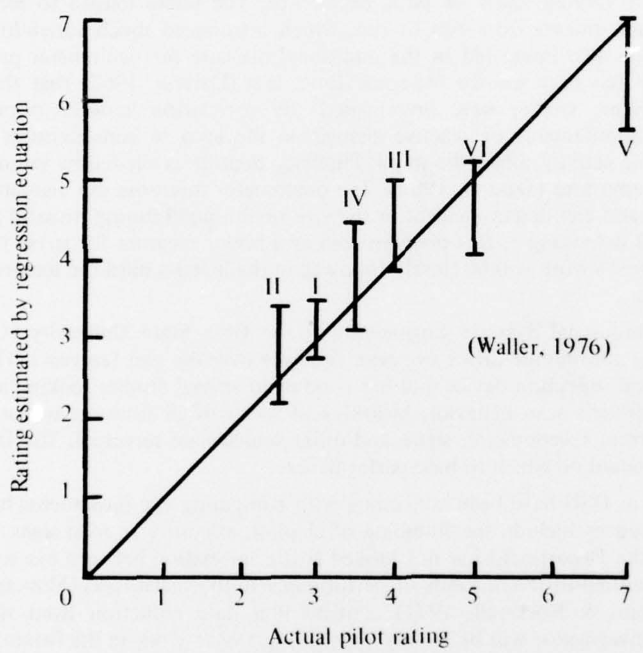


Figure 3. **Comparison of regression analysis rating and actual pilot rating.**

The tabulation of the parameters in Figure 3 would be most lengthy. It would require a frame by frame analysis of the video tape in order to measure dwell times and transition rates to the tenth of a second. In addition, if the NAC were out of calibration, the relative error would have to be considered in the analysis, especially for the condition in which the pilot fixates in turn on the several instruments. The oculometer would be a better instrument to use for such a study since it is computer-based and can score eye data automatically to the hundredth of a second and it has a linearization algorithm to compensate for the pilots's eye irregularities once it has been calibrated. The discussions of the integration and use of such an instrument are presented in Appendix F.

In accomplishing this long-range objective the proposed analysis technique was presented as a first-cut attempt at correlating pilot eye scan and performance. Until research is reinitiated on this effort, the investigator is searching the literature for similar studies and investigations.

The NASA/Langley Research Center has been actively involved in pilot eye scanning research. Their efforts, to date, have been restricted to instrument flight rules (IFR) conditions, only. They have not looked at the problem of how the pilot uses his out-the-window cues. Several studies (Waller, 1976; Waller & Wise, 1975) at Langley have aimed at understanding the pilot as an information processor and decision-maker and at producing a model of this process. Langley is not looking at the varying levels of pilot experience. Although their objectives are different, Langley's success at developing such a model will be closely monitored.

The AMRL has an oculometer which is similar to that used at NASA/Langley. However, their instrument has been used for measuring pursuit tracking experiments only, to date, and AMRL has not investigated pilot eye scan patterns (while flying).

The Systems and Research Division of Honeywell (the developers of the oculometer) has also been investigating pilot's eye scan behavior under ILS conditions. Honeywell has been under contract to NASA/Langley to help develop a model for pilot workload. They are interested in determining what information a pilot uses in making a control input. In a recent study by Honeywell (Krebs & Wingert, 1976), it was determined that individual pilot repeatability varied more than anticipated. More variability was found within the data from each pilot than among the data from different pilots in some instances. Data were not collected on varying levels of pilot experience. The pilots tended to redistribute their attention on the various instruments from run to run, which introduced much variability in the data. Researchers at Honeywell are also interested in the additional measure the oculometer provides, that is, apparent pupil diameter. It has been known for some time now (Davson, 1962) that the eye exhibits pupillary reflex dilation. Some studies have investigated the correlation between pupil dilation and workload (Beatty, 1976). Spontaneous or reactive changes in the level of consciousness or changes in cortico-thalamo-hypothalamic activity dilate the pupil. Pupillary dilation is elicited by sensor or emotional stimuli, or by thoughts or emotions (Davson, 1962). The oculometer monitors the diameter of the pupil throughout the experiment and can detect changes in the size of the pupil during stressful portions of the monitored flight. Honeywell is looking at this phenomenon as a better measure for stress than heart rate, blood pressure, etc. Honeywell's work will be closely followed in the interim until the long-range objectives of this study are investigated.

The Department of Industrial Systems Engineering at the Ohio State University (OSU) has been actively involved in studying automobile driver eye scan behavior over the past ten years. The Department has developed its own corneal reflection device and has conducted several studies looking at the temporal and spatial measures of a driver's scan behavior. Measures of mean dwell time on instruments, fixation times, and transition rates from speedometer, signs, and other vehicles are recorded. The Department has not, as yet, established a standard on which to base performance.

Most of these studies at OSU have been concerned with comparing eye movements before and after an occurrence. Such occurrences include the imbibing of alcohol, exposure to road signs, and receipt of driver's training. Although the Department has not looked at the correlation between eye scan pattern and performance, they have measured different kinds of performance in the visual tasks (Mourant & Rockwell, 1971). OSU studies (Mourant & Rockwell, 1971) confirm that data reduction from video tapes is a time-consuming task. This investigator will be closely monitoring OSU's work in the future. (Editor Note: A 60° FOV NAC was integrated with an actual flight helmet at the Flying Training Division, Air Force Human Resources Laboratory, Williams Air Force Base, Arizona. However, numerous technical problems rendered the data unusable. Additional information can be obtained from AFHRL/FT, Mr. W. D. LeMaster, Williams AFB, Arizona 85224.)

An attempt to accomplish the other long-range objective of this study cannot logically be initiated until some correlation between pilot's eye scan behavior and performance has been found. If we can assume that an acceptable model of pilot workload can be produced from studies using the NAC at AFHRL or the oculometers at Langley Research Center or Honeywell, then an optimal control model (Gelb, 1974) of the pilot's eye scan pattern can be developed. This model could possibly be used initially to train novice pilots how to scan their instruments under IFR conditions. More data would have to be collected under visual flight rules (VFR) conditions to extend the model to out-the-window visual cue training. The first attempt would be to predict expert pilots' eye scan behavior under IFR conditions. Such a model would be configured as presented in Figure 4.

In such a process (Figure 4) a model of the pilot's workload would be the key block in the diagram. If and when such a model is developed, then the final long-term objective of this study could be investigated.

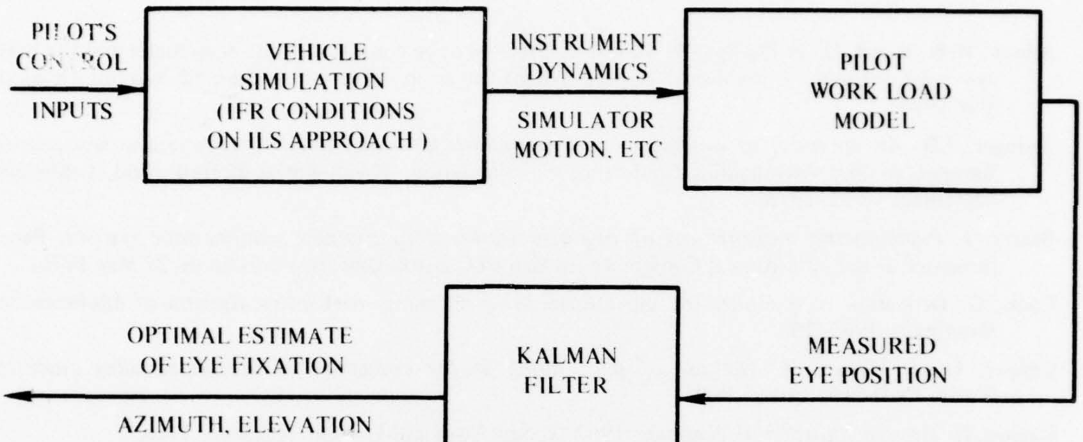


Figure 4. **Optimal control model of eye scan behavior.**

Looking at Figure 4, the approach would be to predict an experienced pilot's regions of high fixation density for a particular simulation (such as an ILS approach and landing). The Kalman filter[3] uses all available measurements, regardless of their precision, to improve the accuracy of the overall data system. It would process the measurements to estimate the current value of the variable of interest, eye elevation and azimuth, with the use of (a) knowledge of the workload model, (b) the assumed statistics of the system noises, measurement errors, and uncertainty in the workload model, and (c) any available information about initial conditions (Maybeck, 1975).

The advantage of the Kalman filter in this application is that it can use the measured eye scan data that are the basis for the pilot workload model and compute a difference between the measured value and the best prediction of what it should be, based on all previous information. This prediction is then passed through a set of optimal gains (Maybeck, 1975) which provide a correction to the optimal prediction of the stated variables of the system's dynamics generated by the model. These variables would include eye elevation and azimuth. For this case of a linear system (pilot workload model) driven by white Gaussian noises (such as wind turbulence), the Kalman filter provides the best possible estimate of eye fixation. These variables could then be used to drive a white dot across a monitor which was displaying the instrument panel. The white dot would locate optimal eye fixations and transitions. The novice pilot could observe this optimal eye scan behavior and the training value could be studied in a research environment.

Such an approach to achieving the third objective of this study is offered in this discussion since the objective has not yet been investigated.

Other researchers (Krebs & Wingert, 1976; Waller & Wise, 1975) have looked at predicting eye fixations but none of these studies were based on using the predicted fixations to train pilots.

---

[3] A Kalman filter is simply an optimal recursive data processing algorithm. It is one of the most common optimal filtering techniques for estimating the state of a linear system (Maybeck, 1975).

REFERENCES

Albery, W.B., Kugel, D., & Phillips, W. Measuring predictive eye control with the oculometer and the NAC eye mark recorder. Unpublished Report, Wright-Patterson AFB, OH: Advanced Systems Di ision, May 1974.

Basinger, J.D. *An approach to computer image generation for visual simulation.* American Institute of Aeronautics and Astronautics Conference on Simulation, NASA-Ames. Moffett Field, California, September 10-12, 1973.

Beatty, J. *Pupillometric measurement of cognitive workload in complex man/machine systems.* Paper presented at the 12th Annual Conference on Manual Control, University of Illinois, 27 May 1976.

Cook, G. Derivation of a model for the human eye-positioning mechanism. *Bulletin of Mathematical Biophysics,* 1967, **29**.

Cooper, G., & Harper, R. *The use of pilot rating in the evaluation of aircraft handling qualities.* NASA-TN-D-5153, April 1969.

Davson, H. The eye. *Muscular Mechanisms,* 1962, **3**. New York and London: Academic Press.

Ditchburn, R.W., & Ginsborg, B.L. Involuntary eye movements during fixation. *Journal of Physiology,* 1953, **119**(1).

Gelb, A. *Applied optimal estimation.* Cambridge, Mass: The MIT Press, 1974.

Jordan, S., & Manfredi, U. *Eye movement research program.* Tech Report NAVTRADEVCEN, IH-202, AD-741 246. March 1972.

Krebs, M., & Wingert, J. *Use of the oculometer in pilot workload measurement.* NASA CR – 144951, February 1976.

Mackworth, J.F., & Mackworth, N.H. Eye fixations recorded on changing visual scenes by the television eye marker. *Journal of the Optical Society of America,* 1958, **48** 439.

Maybeck, P.S. *Stochastic estimation and control systems.* Air Force Institute of Technology Short Course. Wright-Patterson AFB, OH: February 1975.

Merchant, J. *The oculometer.* NASA CR-805. July 1967.

Merchant, M. *A remote oculometer permitting head movement.* AMRL-TR-73-69, AD-776 075. Wright-Patterson AFB, OH: November 1973.

Milsum, J. *Biological control systems analysis.* New York: McGraw-Hill, 1966.

Mourant, R., & Róckwell, T. Visual scan patterns of novice and experienced drivers. Department of Industrial Systems Engineering. The Ohio State University, *Symposium on Psychological Aspects of Driving Behavior*, Netherlands, August 1971.

Robinson, D.A. The mechanics of human saccadic eye movement. *Journal of Physiology,* 1964, **174**, 245-264.

Robinson, D.A. The mechanics of human smooth pursuit eye movement. *Journal of Physiology,* 1965, **180**, 569-591.

Robinson, D.A., O'Meara, D.M., Scott, A.B., & Collins, C.C. Mechanical components of human eye movements. *Journal of Applied Physiology*, May 1969, **26**(5).

Thomas, E.L. The eye movements of a pilot during aircraft landing. *Aerospace Medicine*, May 1963.

Tiffin, J., & Bomer, J. *Analysis of eye fixations and patterns of eye movements in landing a piper cub J-3 airplane.* Report No. 10. Washington, D.C., Div. of Res. February 1943.

Vossius, G. Das system der augenbewegung. *Ztschr. Biol.*, 1960, **112**(27).

Waller, M. *An investigation of correlation between pilot scanning behavior and workload using stepwise regression analysis.* NASA-TM-X-3344. March 1976.

Waller, M., & Wise, M. *The oculometer in flight management research.* American Institute of Aeronautics and Astronautics Aerospace Sciences Meeting, January 1975.

Wasicko, R.J. *Dynamics of the eye servo system.* Wright-Patterson AFB, OH: Aerospace Mechanics Branch, Aeronatutical Systems Division, Flight Control Laboratory, April 1962.

Westheimer, G. Mechanism of saccadic eye movements. *American Medical Association Archives of Opthalmology*, 1954, **52**, 710-724.

Young, L.R. Measuring eye movements. *The American Journal of Medical Electronics*, October – December 1963.

Young, L.R., Zuber, B.L., & Stark, L. *Visual and control aspects of saccadic eye movements.* NASA CR-564, September 1966.

APPENDIX A: ANATOMY OF THE EYE MUSCLE SYSTEM

At least two neural systems control the eyeball's position at any instant. These are the versional and the vergence control systems. The versional system controls tracking of a target moving in a plane perpendicular to the visual axis; the vergence system controls the angle between the visual axes of the two eyes so that corresponding regions of the two retinas receive the target image at each instant. The orientation of the eye with respect to the head is controlled by the six extraocular muscles, which can cause it to rotate about a point approximately at its geometrical center. The six extrinsic muscles of the eye are admirably suited for their task of rotating the eyeball (Davson, 1962). They are arranged in three pairs of muscles as shown in the dissection view of Figure A1. In any eye movement one of the muscles of any pair (the agonist) contracts to pull on the eyeball while its opposite member (the antagonist) relaxes but opposes the motion. The movements of the eyeball are generally defined in terms of primary axes of rotation of the eyeball about its center. In rotations about the vertical axis the cornea moves laterally, away from the nose (abduction), or medially, toward the nose (adduction). Rotations about the transverse axis running horizontally right to left, move the cornea up (elevation) or down (depression). The third axis, the sagittal axis, is defined as the primary line of vision, and rotations about it rotate the top of the cornea nasally (intorsion) or laterally (extorsion). The axes of rotation determined by the individual muscle pairs, however, are nonorthogonal, and do not line up with the primary axes. As a result, the muscles have subsidiary actions as well as main actions. The possible actions of the muscles are shown schematically in Figure A2, for the eyes looking straight forward. Thus, the lateral and medial recti are an opposing pair used for adduction and abduction only, regardless of eye position. The superior rectus, on the other hand, has a main action in elevation, which increases as the eye turns out and decreases as the eye turns in, and also subsidiary actions of adduction and intorsion which become increasingly important as the eye turns nasally.

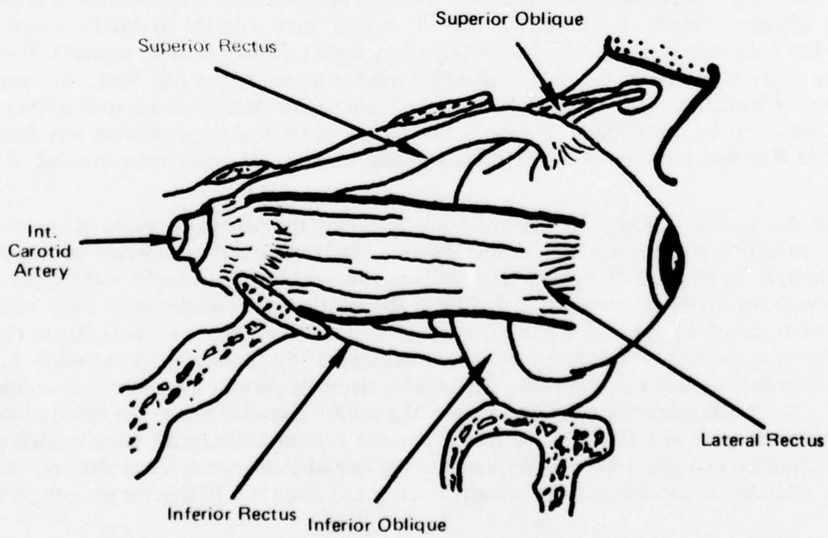


Figure A1. **Dissection view of eyeball and extrinsic muscles.**

PRECEDING PAGE BLANK-NOT FILMED

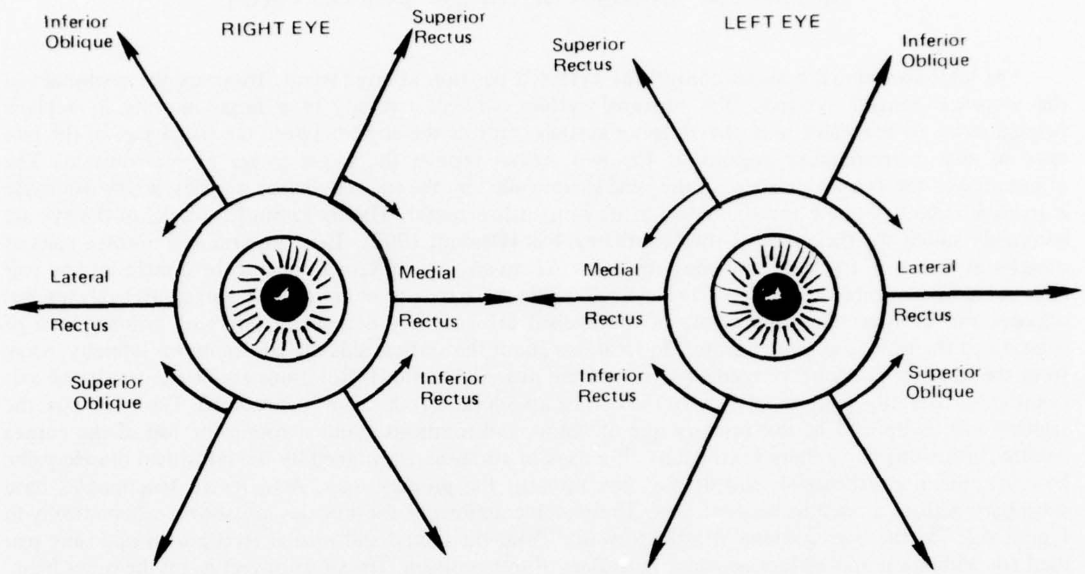


Figure A2. **Schematic diagram of extraocular muscle actions.**

The normal muscle fields permit the eye to rotate about 45° left or right, 40° up and 60° down, and 30° in extorsion or intorsion. Since the muscle pairs are attached approximately at ends of diameters of the eyeball, their action is enhanced by a mechanical advantage not generally found in other muscles of the body. The extrinsic muscles are about 100 mm^2 in cross section; their maximum force is calculated to be nearly one kilogram weight (2.2 lbm), whereas the actual force required to initiate a moderate saccadic movement has been calculated as less than 100 grams weight (.22 lbm or 6.25 ounces). This large reserve force means that only some of the individual fibers need contract at any one time, allowing the others to rest. The nerves which transmit commands from the brain to the extraocular muscles contain a great many fibers in proportion to the number of muscle fibers they control, thus permitting very fine control over these muscles. The reaction time of the extrinsic muscles, less than 10 msec, is the shortest of any muscle in the body.

All of the passive elements of the eye orbit, including the passive elements of the muscles, form a visoelastic restraining medium for the globe (Davson, 1962). The spring constant of this medium is 1.2 gram/deg. Simply to displace the globe 10 degrees in this medium the muscles must apply a force of 12 grams. Likewise, to rotate the globe at 10 deg/sec in this medium the muscles must apply a differential rate of change of force of 12 grams/sec plus a force to overcome the viscous friction. These elements of the medium represent the major impedance to sudden motions of the globe and far outweigh the effect of the very small moment of inertia of the globe. These same elements prevent the globe from coming to rest in a new position until 500 msec after the application of a sudden constant force. The speed of response of the globe's rotation is increased through the central nervous system utilizing the large tension reserve of the extraocular muscles to cause a burst of excess force or rate of change of force to alter eye position in only 45 msec in a 10 degree saccade and eye velocity in only 133 msec in a 10 deg/sec smooth pursuit response.

APPENDIX B: OCULOGRAPHY: THE RECORDING OF EYE MOVEMENTS

Oculography is the observation and recording of eye movements. The state-of-the-art has progressed from bulky, mechanical devices which attached directly to the eyes to the modern oculometer, a non-restrictive device made possible with advanced electro-optics and the digital computer. In this section, the history of oculography (Young, 1963) will be summarized, the various types of eye movements will be characterized, and the methods used to measure these eye movements over the last 100 years will be discussed. Two pieces of equipment will be introduced: (a) The NAC eye-mark recorder, a corneal reflection device, and (b) The oculometer, an electro-optical device. The oculometer represents the state-of-the-art in oculography.

The measurement of eye position provides useful information to investigators in several different fields. To the medical profession, eye movements can serve as a diagnostic aid in treatments affecting the oculomotor system or as an aid in diagnosing or treating schizophrenics, for example. The psychologist is interested in investigating the reading habits of children; monitoring eye movements is one method available to him. Eye movements provide the human engineer with an aid in evaluating the human suitability of instrument panel and control designs. Advertising men evaluate the effectiveness of their displays by monitoring customers' eye movements. Various researchers in the Air Force are particularly interested in the eye movements of pilots. Since no one really knows what to tell a student pilot to watch for in learning to land an airplane, perhaps by monitoring experienced pilots' eye movements and learning what visual cues they use and teaching the students to use the same visual cues, eye movement studies can be used to enhance training.

Seven types of eye movements have been identified: (a) Saccadic or fast movements are the little jumps by means of which we voluntarily move our eyes conjugately from one fixation point to another. Characterized by a reaction time of 120 to 250 msec, they may be larger than 50° with a velocity as high as 600°/sec; (b) Pursuit movements are the slow conjugate tracking movements, 1 to 30°/sec, with which we follow a slowly moving target; (c) Compensatory movements are smooth (30°/sec) movements of the eyes to compensate for active or passive movements of the head or trunk; (d) Vergence movements involve the motion of the two eyes in opposite directions in order to lock-in the images of a near or far object on corresponding retinal points and permit binocular vision. These cover a range of approximately 15° and reach velocities of the order of 10°/sec. (e) Miniature movements, less than 1° in amplitude, fall into three classifications. Drift is the tendency of the eye to move slowly away from the fixation point in a random direction with a velocity of several minutes of arc/second. Flicks are rapid saccadic-like movements, occurring at intervals as short as 30 msec, which tend to be opposite to the direction of drift and to keep the fixation point in the 1° central FOV. Tremor is small, high frequency motion in the range of 30 to 150 cps and peak amplitude of approximately 30 arc seconds at 70 cps. (f) Rolling or torsional movements of the eye about the line of gaze are compensatory in nature and entirely involuntary. They are slow, tend to lag behind by angles up to 30°, and are apparently stimulated by the semi-circular canals. (g) Nystagmus is a general term applied to a large class of eye movements of an oscillatory or unstable nature. Among the most common types are optokinetic, vestibular, and spontaneous nystagmus.

The variety of methods developed for the observation and recording of eye movements indicates the interest in this subject by investigators from many different fields. A large number of techniques have been developed, each with its own characteristics of range, sensitivity, bandwidth, stability, and ease of application.

Much of the early (circa 1870) quantitative work on the duration and nature of eye movements was done by using after-images (Young, 1963) of a bright light to indicate the characteristics of the movement. The principle is that the images of a regularly flashing light will leave a series of after-images on the retina. The number and spacing of these after-images, as subjectively reported by an experienced subject, indicate the duration and velocity of the movement. If the light is on steadily during a movement, the presence of a sequence of bright spots or nodes as the after-image indicates the number of fixation points, separated by saccades. Since this method permits eye movements up to ±45° from the light source, and still allows for resolution of after-images separated by less than 15 minutes of arc, it offers one of the largest dynamic ranges of all methods of investigation. Its chief drawback, that it is subjective and yields no record of eye movements, caused it to fall into disuse when improved objective technqiues became available.

In an effort to achieve objective permanent recording of eye movements, a number of ingenious mechanical devices were developed to detect and record these motions. In the earliest attempts, around 1898, a light rod (Young, 1963) was attached directly to the cornea of an anesthetized eye by means of a glass bead or plaster of paris. The mechanical motion of the rod was transformed through a series of levers to record the motion on the smoked paper of a rotating drum keymograph. Vertical motions were similarly recorded by tying levers to eyelids, the attachment being made with tape.

In later developments, around 1912, the protuberance of the cornea (Young, 1963) was used to activate mechanical devices, either directly or through pressure transducers that sensed the change in air pressure as the corneal bulge pressed against the membrane during eye motion. These instruments were usually designed to be placed over the lid of one eye, with the other eye open. These methods inherently interfere with normal eye movements although they set an early standard for quantitative recording of eye movements.

In order to make objective recordings of eye movements without the interference that is inherent in mechanical transducers, direct photographic records of eye position were used. In 1899, the image of the subject's eye was focused on a vertical photographic plate (Young, 1963) which was constrained by the viscous forces of an oil bath to fall at a constant velocity. Displacements of the light-dark boundary between the sclera and iris yielded a continuous record of horizontal eye movements in 1906 (Young, 1963). The method was improved with the development of continuous film drives capable of handling longer lengths of film. This method was then advanced by photographing only that portion of the eye to which some bright foreign material had been attached (Young, 1963). All of these methods required that the head position be accurately fixed, and they consumed vast quantities of film for accurate recording of essentially intermittent movements. Such methods would be impractical in the flight training environment of an aircraft cockpit.

A special case of this direct photographic recording is the corneal reflection method. Because of the smooth, spherical front surface of the cornea, an incident beam of light will be partially reflected to form a bright spot, or "highlight" on the cornea (see Figure B1). Note the relative differences in the radii of the eyeball and cornea. On the right, note the circle in the center of the cornea; this highlight serves as the

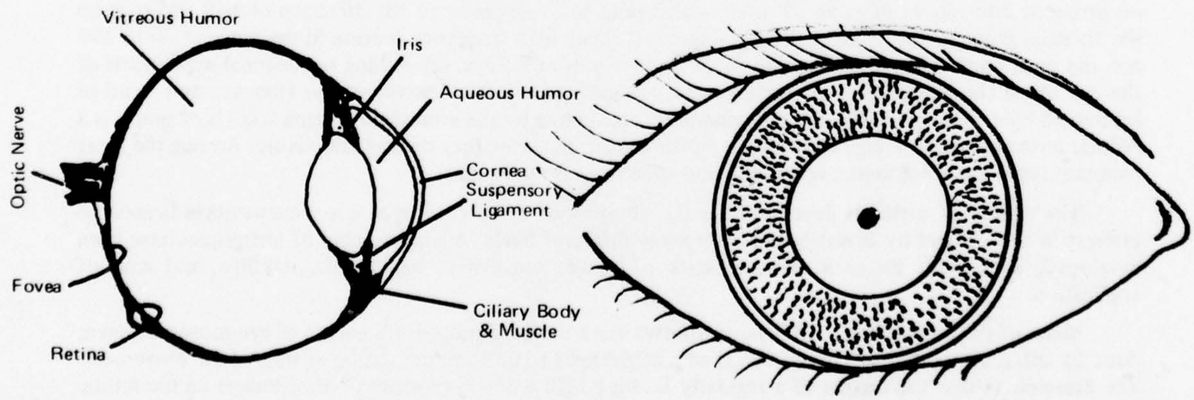


Figure B1. **Highlight of human eye-corneal reflection.**

necessary input to corneal reflection devices such as the NAC EMR. Incident rays of light are partially reflected off the cornea to form the bright spot, or highlight. The angle of the reflected light depends upon the angle between the incident light ray and the normal to the reflecting surface. Since the cornea forms an

eccentric bulge on the nearly spherical eyeball, the normal to the cornea at any one point in space changes as the eye rotates about its center during an eye movement. As a result, the position of the highlight moves in the same direction as the cornea, but with approximately one-half of the amplitude. The reflected beam is easily recorded, either on film or video tape. This method is convenient for large-scale testing on untrained subjects, since no interference with normal eye movements is associated with it.

There are two basic limitations to the corneal reflection method. First, the linear range of the method is restricted to approximately $\pm 12.5^\circ$ by the limited extent of exposed cornea and the nonspherical nature of its surface at its periphery (see Figure B1). Second, the disturbance resulting from lateral head movements is more serious than with any of the other methods, if the device is not attached directly to the subject. An expression for PHI, the angular displacement of the reflected beam of light, as derived by Ditchburn and Ginsborg (1953) is:

$$\text{PHI} = 2((A/a - 1)*\text{THETA} + d/a)$$

where A = radius of curvature of the eye (c. 13.3 mm.); a = radius of curvature of the cornea (c. 8.0 mm.); THETA = angular displacement of the eye; and d = lateral displacement of the head. A lateral displacement of 0.1 mm would induce an error in measured eye position of approximately 1°.

The primary instrument used in this thesis study was the NAC Eye-Mark Recorder, a corneal reflection device developed in Japan and developed first to evaluate visual field points of interest in railroad simulators. This electro-optical instrument is extremely versatile with numerous applications and has the feature of being head-mounted, which holds at zero the "d" in Ditchburn and Ginsborg's (1953) equation. The device is light-weight because there is no camera mounted to the user's head. All video information is transmitted by fiber optics to a remote recorder (camera, monitor, etc.) (see Figure C1). The NAC simultaneously and continuously records the subject's discrete visual point of gaze within his FOV. This is achieved by reflecting an illuminated spot off the cornea and superimposing the reflection onto the field of view. Both FOV and the superimposed illuminated spot are then recorded on 16mm motion picture film or closed circuit TV, or can be visually observed.

In 1953, a contact lens technique was developed whereby a contact lens was fitted over the cornea (Young, 1963) and the image of a light source was reflected by a small plane mirror mounted on the corneal lens. This method is by far the most sensitive and has yielded good records of eye movements of less than 10 seconds of arc. There are several inherent advantages of the contact lens reflection method over the corneal reflection technique. The reflected beam moves through twice the angle of eye rotation and the use of a plane mirror eliminates the artifacts resulting from irregularities in the frontal surface of the cornea. Furthermore, since the plane mirror is displaced parallel to itself by translational head movements, this method is much less sensitive to head movements than the corneal reflection method if the device is not head mounted. The obvious disadvantage of this technique is the necessity of placing a foreign object on the eye. Although the additional moment of inertia is very small compared with that of the eyeball, it is difficult to maintain that no interference with normal eye movement occurs.

As early as 1922, it had been demonstrated that certain electrical changes are associated with eye movements (Davson, 1962). It was not until more recently that the nature of these changes was understood and the electronics for detecting and recording them was developed. To use this technique to record eye position, one places silver-silver chloride EEG electrodes (Davson, 1962) on the inner and outer canthers of each eye (for horizontal movements) and/or above and below the eye (for vertical movements). The method is useful and convenient for recording movements in the range $\pm 1/2^\circ$ to $\pm 40^\circ$, and has been extended to record eye movements of $\pm 90^\circ$. The disadvantages (Davson, 1962) of this technique include eye-blinks (which distort the record of eye position) and electrical artifacts of drift. The most serious disadvantage of the electro-oculographic technique, however, is crosstalk between axes of motion. In other words, the electrical record of eye positions will indicate a change in vertical position (for example) even though the task was a pure horizontal movement. Davson (1962) attributes this anomaly to the fact that the eyes, in a normal change of fixation, move with a screw motion.

The photoelectric (Young, 1963) measurment method was developed around 1958 and it uses photosensitive devices to measure eye position. The position of the limbus, or boundary between the white sclera and dark iris, is optically detected and this signal is converted into a voltage which may be easily recorded on an oscilloscope or pen recorder. Such devices entail no interference with normal eye movements and are limited in their frequency response only by the bandwidth of the electronics.

An electro-optical system which dynamically measures pupil diameter and human eye movement was developed at Honeywell in the early 1960's. The oculometer (Merchant, 1967) is a non-restrictive, computer-based oculographic device which enables an experimenter to determine not only what the subject is looking at, but what the subject's pupillary response is to that particular stimulus. The basic sensing principle of the oculometer is that eye direction is defined by the position of a corneal reflection (of the radiation source within the oculometer) relative to the center of the pupil. The electro-optical sensor unit is located several feet from the subject, who is free to move the eye being sensed throughout a cube in space one foot on a side. The displacement of the corneal reflection from the center of the pupil is K Sine θ (Figure B2) where θ is the angle between the geometric axis of the eye and the direction of the incident collimated beam (which is a reference direction, the optical axis of the oculometer), and K is a dimensional constant of the eye. Displacement of the corneal reflection from the center of the pupil by K Sine θ is proportional to the angular direction θ of the eye, and is independent of the position of the eye. Thus, by measuring in the eye image the displacement of the corneal reflection from the center of the pupil, a measure is obtained of the direction of the geometric axis of the eye. The displacement between the center of the pupil and the corneal reflection is independent of the position of the eye. That is, if the eye moves (with no rotation), the displacement between these two points is invariant. The displacement between the rays is solely a function of the angular direction of the eye.

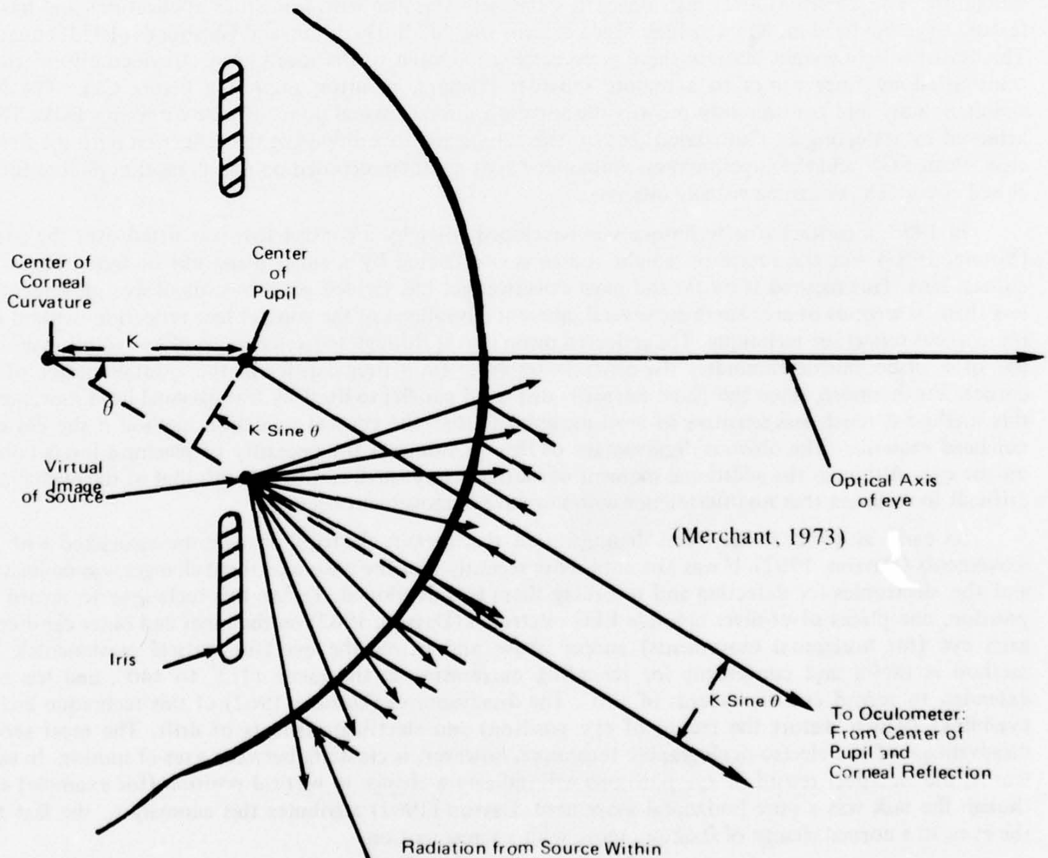


Figure B2. **Basic sensing principle of the oculometer.**

Among the many techniques which have been utilized for measurement of eye movements, some have been superseded by technological advances whereas others have maintained their usefulness for certain applications. The currently popular methods may be classified by the range of eye movements over which they find their most useful application.

For the detection and measurement of miniature eye movements, or those less than 1°, the most precise measurements in this range are generally made with a contact lens fitted to the cornea or over the entire sclera. Reflections from a mirror mounted on the lens can yield precision of a few seconds of arc, but the accurate range is limited to movements of less than 5° by slippage of the lens. This error becames more significant at larger angles. The corneal reflection principle is generally limited to $\pm 12.5^\circ$ by the size of the corneal bulge, but may be applicable to miniature eye movements depending on the type of the device. The NAC can be calibrated to accuracies of much less than 1° over a range of $\pm 10^\circ$ horizontally and vertically. Beyond $\pm 10^\circ$, the reflected light source is located on the nonspherical and rougher peripheral portion of the cornea and as a result the accuracy of fixation is degraded. The oculometer has an accuracy of approximately 1° over a field of view of -10° and $+30^\circ$ vertically and $\pm 30^\circ$ horizontally; however, jitter in the digital mode of tracking the eye makes this system unsuitable for the task of measuring miniature eye movements of less than 1°.

Eye tracking movements in the range of 1° to 20° are measured best by the oculometer because of its accuracy and non-restrictive nature. Photoelectric, electro-oculographic, and corneal reflection devices are also applicable in this range. The differential reflection devices offer the advantage of being small and light enough to be mounted on goggles, glasses or a helmet and worn by the subject, thereby permitting free head movement. Such is the case with the NAC eye recorder in this study.

For excursions so large that the limbus becomes hidden behind the lid (greater than 20°), the oculometer and electro-oculography appear to be the most promising methods, although some of the photoelectric techniques can be extended to this range. In one version of the oculometer, the Mark III, the subject is permitted one cubic foot of head motion volume and the tracker can still maintain eye position/location (Merchant, 1973).

APPENDIX C: NAC EYE-MARK RECORDER

A NAC eye-mark recorder was obtained from the Aerospace Medical Research Laboratory, Wright-Patterson AFB, Ohio, and used at AFHRL to conduct basic eye movement research, (eye response data from Table D1 were taken, and in a simulator, where the performance of the instrument was investigated).

The device provides both a 60-degree view of the scene directly forward of the pilot's momentary head position and an indication of his fixation point within the scene. The NAC recorder is an optical device in which an illuminated reticle which is reflected off the cornea by movement of the eyeball can be aligned with the visual line of regard. This reticle then is superimposed on a primary image of the scene directly forward of the pilot and may be recorded on a 16mm film or video tape or be viewed on a monitor. The NAC is equipped with a lens having a 60-degree FOV which is adequate for recording the forward visual environment of the pilot, particularly since the lens travels with any head movement. The video tape recorder, in both the aircraft and the simulator(s) would appear to be the most advantageous recording medium because of its capability for instant replay.

Two subjects were used in the experiment and one wore contact lenses. The contact lens affected the corneal reflection only at eye angles greater than 10° off-axis where multiple reflections occurred (eyeball and contact lens). The resolution of the 30° type NAC is twice that of the 60° type (twice the visual information being transmitted over the same number of fiber optic bundles.) The bundle itself is comprised of a 4 x 5 mm, 200 x 250 strand matrix which means that the maximum possible vertical resolution is:

(22.7 deg x 60 minutes/deg)/200 strands = 6.81 arc min

The maximum possible horizontal resolution is:

(31.4 deg x 60 minutes/deg)/250 strands = 7.536 arc min .

The manufacturer lists the 30° type vertical and horizontal field-of-views as 22.7° and 31.4°, respectively. The 60° type NAC has specified vertical and horizontal field-of-views of 43.5° and 60°, respectively, with associated resolution capabilities of 13.05 arc min vertically and 14.4 arc min horizontally. The ASPT visual display has a resolution of less than 7 arc min and as a result, some detailed position elements may be lost using the 60° type NAC which has one-half the resolving power of the display. Still pictures were taken from a monitor-playback of recordings made in the AFHRL/Advanced Systems Division simulator and visual cues in the display as well as instruments on the panel are easily recognizable. Since the video camera was not a low-light-level device, the contrast of the visual display had to be increased and the instrument panel had to be brightly illuminated in order to distinguish details (Figures C1 through C3). The picture (eye-mark on simulated runway – Figure C2) was taken off the TV monitor from a recording of the experiment in Figure C1. The chart (Figure C3) on the top was taken through the system with a regular video camera lens. The photo at the bottom is with the fiber optics cable and the 30° NAC camera lens. Note the graininess of the symbols around the edge of the picture. The fiber optics cable is a bundle of 50,000–20 mm fibers with an effective picture area of 4 x 5 mm. The 30° NAC has a maximum power of approximately 7 arc minutes; the 60° NAC, about 14 arc minutes.

Figure C1. **30° NAC Eye-Mark Recorder in simulator** at AFHRL/AS, Wright-Patterson AFB, Ohio.

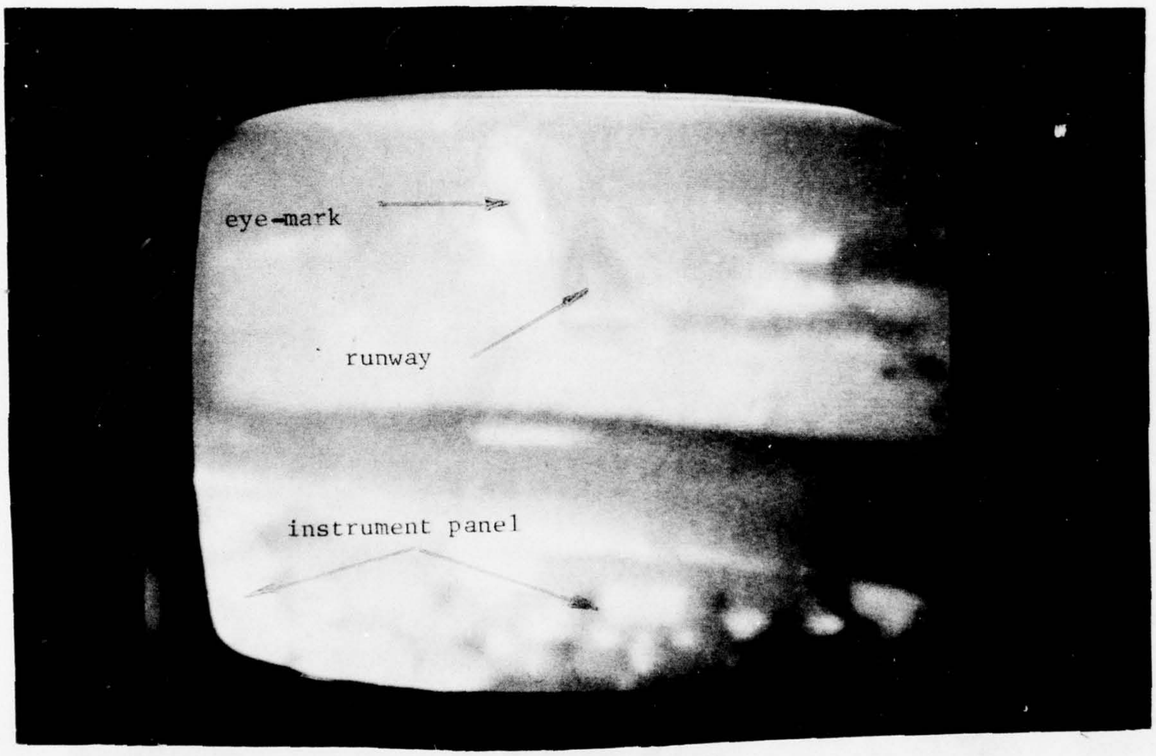


Figure C2. **Eye-Mark on simulated runway.**

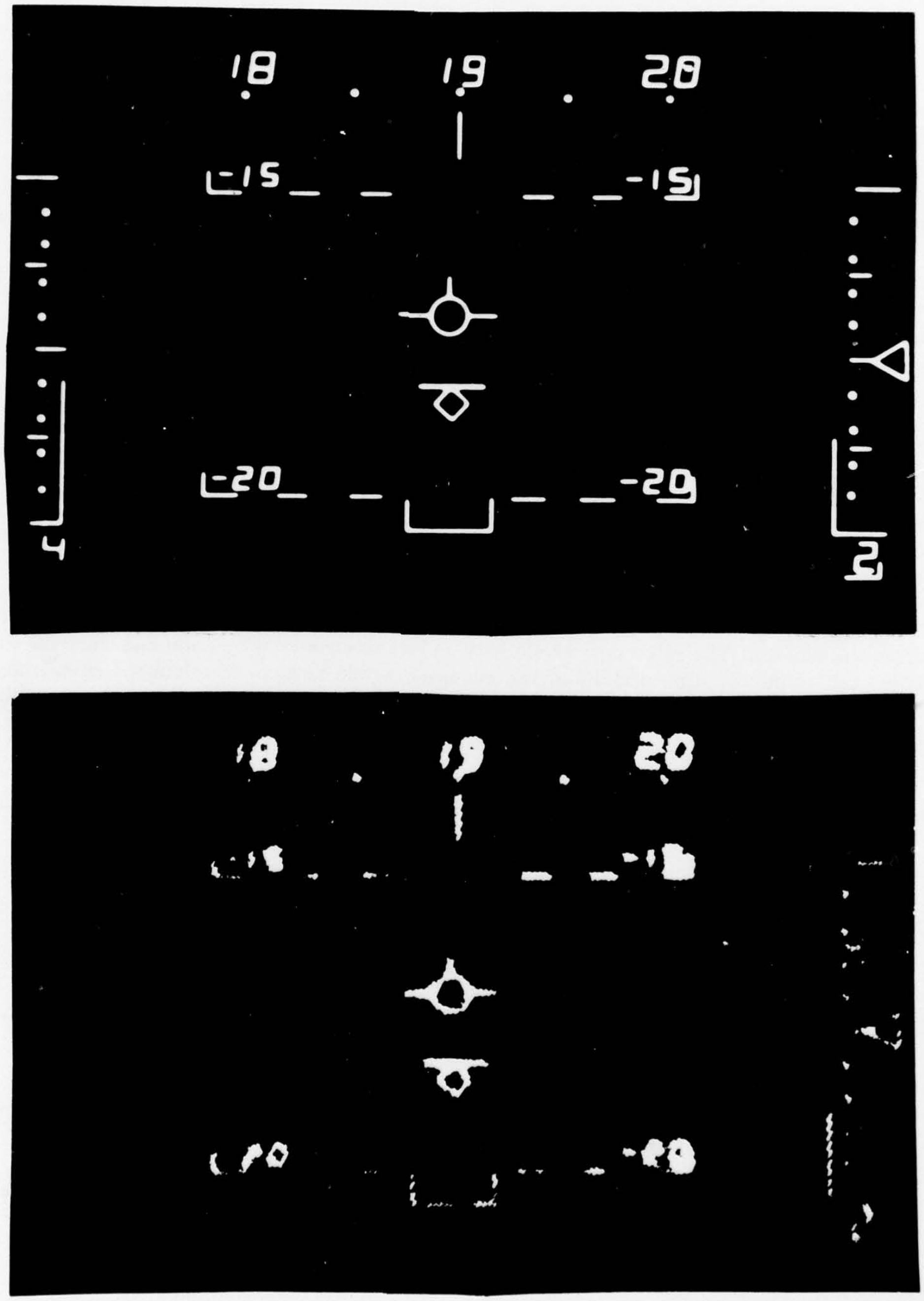


Figure C3. **Resolution chart of 30° NAC EMR.**

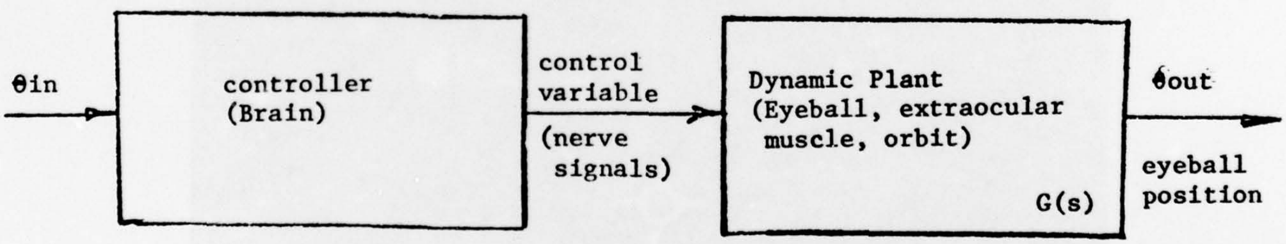
APPENDIX D: NAC/OCULOMETER RESULTS AND MODELS

Using both the NAC eye-mark recorder and the Honeywell oculometer, eye tracking movements were measured using a horizontally aligned sinusoidal stimulus. Vertical and oblique eye-tracking were also investigated (Albery, Kugel, & Phillips, 1974) but will not be discussed in this report.

The oculometer data were collected using the Aerospace Medical Research Laboratory's facility at Wright-Patterson AFB. Three subjects were given the task of tracking a predictable, horizontal ±10 degree sinusoid at five different frequencies: 0.75 cps, 1.00 cps, 1.25 cps, 1.50 cps, and 1.75 cps. The oculometer recorded the azimuth and elevation of both the target and the eye at a 30 per sec iteration rate. An oscillograph recording of each trial was also taken. The data used in this study are taken from one subject in that study.

The NAC data were taken in an effort to verify the oculometer's results and also to gain information about two other directions of tracking investigated less often, vertical and oblique.

The linear, second order system models (Figure D1) developed are derived from the oculometer data. The magnitude of the response to the different frequency inputs was scored by comparing the relative size of the eye output, θ_o, to the constant, relative magnitude of the input sinusoid, θ_i. The magnitudes were then converted to db and the measured phase angle is expressed in degrees. The horizontal data for the NAC are the averages of the values for subjects tested. These data, video recorded and played back on a TV monitor, were measured in much the same manner, comparing the relative magnitudes of the output eye-mark and the input sinuoid signal (which is driven by an oscillator fed into an oscilloscope) at the various frequencies. Phase angle information was not measured on the NAC. These data were difficult to obtain from the monitor. The video tape would have to be analyzed point by point and when the sinusoid reached its peak amplitude, the location of the eye-mark would have to be calculated compared to the input signal. Based on a full amplitude of 180°, wherever the eye-mark was located on the input signal, it would be some value greater or less than 180°. Only oculometer phase data are presented.



Dynamic Plant

Amplitude Model, $$G(s) = \frac{1}{(s/11)^2 + \frac{2(.6)s}{11} + 1}$$

Phase Model $$G(s) = \frac{1}{(s/15)^2 + \frac{2(.4)s}{11} + 1}$$

Figure D1. **Albery's composite model from eye data.**

Evaluating the oculomotor system as a linear servo system, the frequency response data from Table D1 can be analyzed in at least three ways: amplitude ratio fit, phase angle fit, or combined amplitude ratio and phase angle fit.

Table D1. **Frequency Response Data**

Frequency		Amplitude Ratio (AR)				Phase Angle (degrees)
		Oculometer		NAC		
cps	rad/sec	AR	db	AR	db	Oculometer
.75	4.71	1.0	0	1.0[a]	0	−14.5
1.00	6.28	1.0	0	1.0[a]	0	−23
1.25	7.85	.95	−.445	.79[a]	−2.05[a]	−34
1.50	9.42	.89	−1.01	.63[a]	−4.01	−50
1.75	11	.67	−3.48	.54[a]	−5.35	−73
2.00	12.57	–		.29[a]	−10.75	–
2.25	14.14	–		.235[a]	−12.58[a]	–

[a]denotes average of two runs. $\text{db} = 20 \log_{10} (\text{AR})$.

One fit for the amplitude ratio data results in the following approximate eye servo system transfer function:

$$\frac{\theta_o(s)}{\theta_i(s)} \cong \frac{1}{\frac{(s)^2}{(11)^2} + \frac{2(.6)s}{11} + 1}$$

One can see that the corresponding phase angle frequency response for this transfer function differs considerably from the experimental data (Figures D2 and D3). The dots (Figure D2) represent data from the oculometer; the circles, the NAC eye recorder. Note the phase data's transfer function does not fit the amplitude ratio's data. Figures D2 and D3 represent eye tracking performance of individuals following a predictable ±10° horizontal sinusoid.

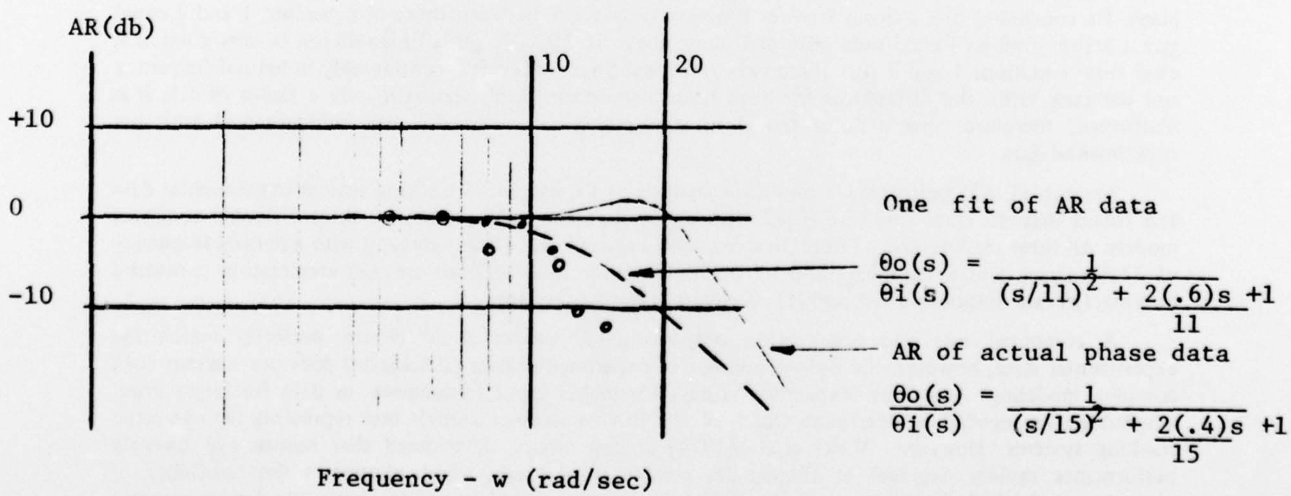


Figure D2. **Frequency response data from eye tracking experiments – magnitude.**

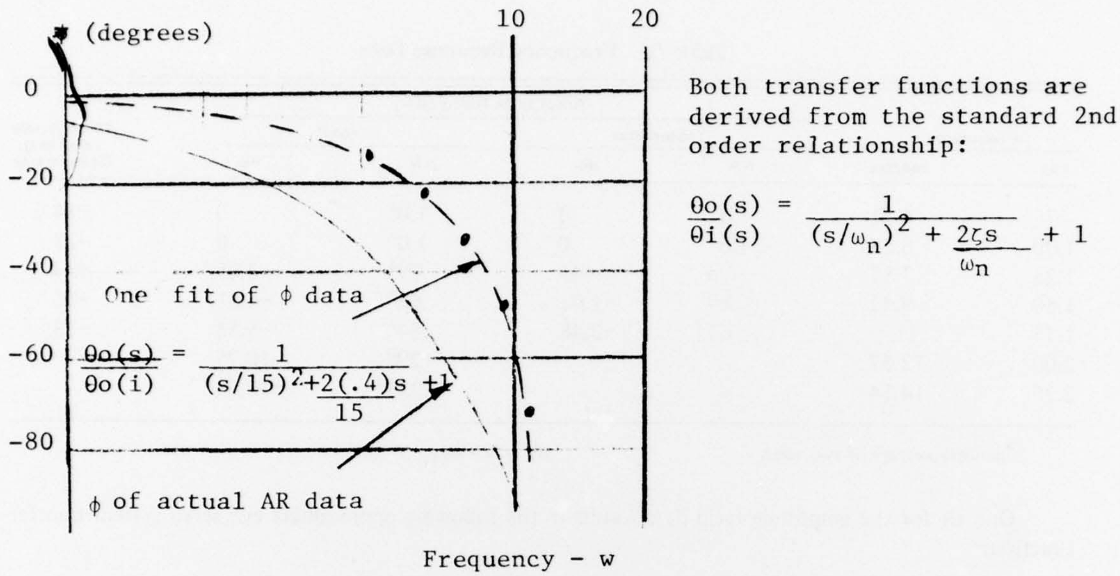


Figure D3. **Frequency response data from eye tracking experiments – phase lag.**

The fit for the phase angle data results in the following approximation:

$$\frac{\theta_o(s)}{\theta_i(s)} \cong \frac{1}{\frac{(s)^2}{(15)^2} + \frac{2(.4)s}{15} + 1}$$

The amplitude ratio frequency response for this transfer function does not match the experimental data very well.

Wasicko (1962) found this same anomaly in the analysis of eye data on a 4.5° sinusoid in a horizontal plane. He concluded that a linear transfer function somewhere between those of equations 1 and 2 could give a better combined amplitude ratio and phase angle fit. However, this fit would not be very good; it is clear from equations 1 and 2 that these two individual "best" fits differ considerably in natural frequency and damping ratio, the differences for both these parameters being approximately a factor of 1.5. It is reaffirmed, therefore, that a linear model for the eye servo system will not compare well with the experimental data.

Wasicko (1962) performed a nonlinear analysis of the eye servo tracking system experimental data and found that the data could be fitted with about the same rms accuracy by three different nonlinear models. All three models have a limiter in series with a second order linear element with a natural frequency of 21.5 rad/sec and a damping ratio of 0.25. The three nonlinearities are: (a) acceleration command limiting, (b) rate output limiting, and (c) acceleration output limiting.

A combined rate and acceleration output limited model could almost perfectly match the experimental data; however, the limited amount of experimental data (2 subjects) does not warrant such complex modeling. Additional experimental data for higher input frequencies, or data for larger input amplitudes, are needed to determine which of the three nonlinear models best represents the eye servo tracking systems. However, Albery et al. (1974) among others, determined that human eye tracking performance rapidly degrades at frequencies greater than 2 cps, which eliminates the possibility of obtaining useful high frequency data. Furthermore, the eye recorder used to obtain the data is accurate only in the range of ±10°. This, then, precluded using input amplitudes greater than ±10°.

In separate experiments, Albery et al. (1974) determined that horizontal and diagonal (oblique) tracking tasks are performed better than vertical tasks because of experience in those modes as opposed to

vertical pursuit movements. The Navy (Jordan & Manfredi, 1972) found that horizontal, ocular pursuit tracking improved with training; and, that some improvement in tracking occurs with all tracking tested, with horizontal tracking showing the largest improvement over vertical and oblique directions of target movement.

Eye Movement Mechanism Models

Several investigators (Young, Zuber, & Stark, 1966) have attempted to describe the mechanics of the eye movement control system using a variety of simplified assumptions and hypotheses concerning the physiological mechanisms. This section will examine several of these control schemes and will compare these models with that developed by the author from empirical data in Table D1. The purpose of a model is not only to predict system behavior in new situations but also to bring about a better understanding of the system.

The first and perhaps simplest model assumes that the eyeball is restrained by muscles which act like linear springs and that its rest position is that at which the active force exerted by the muscles just balances the spring force. Westheimer (1954) proposed such a model and suggested that the motion could be described in terms of a second order linear differential equation:

$A_2\ddot{\theta} + A_1\dot{\theta} + A_o(\theta - \theta_c) = f(t)$ where

A_2 = eyeball moment of inertia

A_1 = the coefficient of friction (viscous)

A_o = the elastic restraint exerted by the relaxed antagonist muscle as the eye's position is changed

θ = eye position

θ_c = some central stable condition

$f(t)$ = the forcing function applied by the agonist muscle.

If one assumes f(t) is a step input, which would correspond to a saccadic eye response, the values of the natural frequency, ω_n, and damping constant, ζ, can be determined, and they are:

ωn = 240 radians/sec

ζ = 0.7

Westheimer (1954) pointed out the existence of nonlinearities in the viscous term and in the tension vs. extension relationship of the opposing muscle in his open loop model, but left these nonlinearities out of his model.

Vossius, (1960) proposed a basically different eye movement mechanism; he claimed that an inner loop proprioceptive feedback mechanism for the muscle spindles on the extraocular muscles controlled individual saccadic jumps. The model proposed by Vossius is drawn in Figure D4. Like Westheimer's model, however, Vossius' model is linear and it makes no allowance for the nonlinearities apparently present in the system.

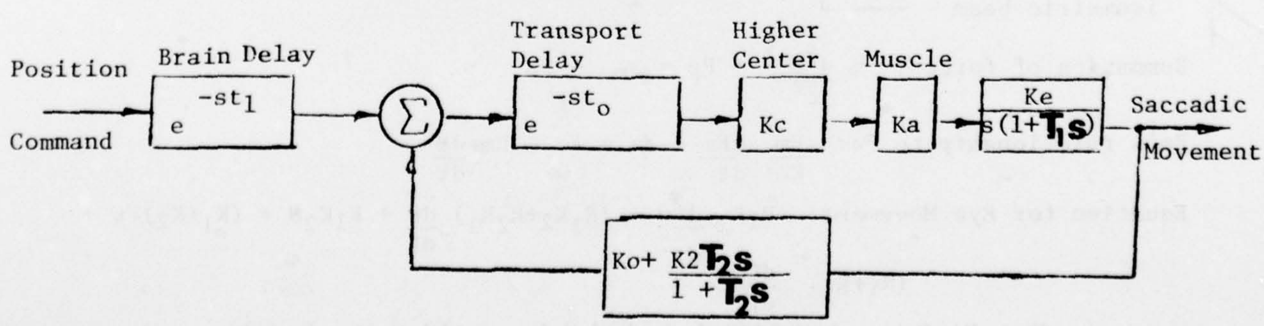
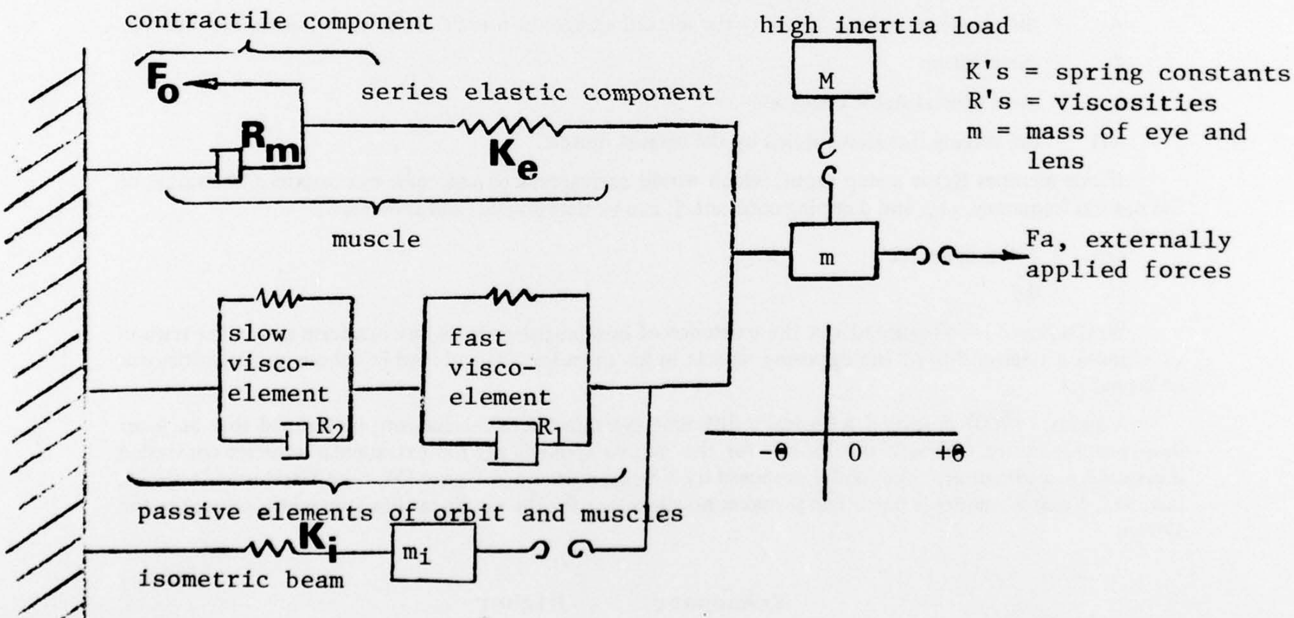


Figure D4. **Vossius' model for saccadic eye movement.**

Robinson (1964) proposed a possible control model based for the first time on experimental data. Models developed previously were based on a limited amount of physiological data on humans. By restraining the left eye from moving through a contact lens and measuring the force applied by the eye to the restraint, while the unencumbered eye made a normal movement, Robinson was able to obtain forces measured in grams at the edge of the eyeball. The 1964 saccadic eye movement study was followed by Robinson (1965) with a smooth pursuit eye movement study. Robinson concluded from both studies that the same static dynamic relation between net active-state tension and globe rotation exists for both saccadic and smooth pursuit movements. The passive spring stiffness of the orbit was revised from 1.5 gram/deg to 1.2 gram/deg in the 1965 study. Robinson, O'Meara, Scott, and Collins (1969) performed experiments on the lateral recti of patients with the principal goal of the study being to obtain the length-tension relationship of human extraocular muscles at various levels of innervation. An important finding of this 1969 study was that L_o, the muscle length for maximum tension, lies at a muscle length greater than L_p, the muscle length with the eye in its primary position, by an amount corresponding to an angular deviation of about 32 degrees. Before this discovery, investigators (Robinson, 1964, 1965; Robinson et al., 1969) had assumed for lack of evidence that L_p and L_o coincided. Robinson's model, shown in Figure D5, accounts for all of his reported observations. The globe is a mass having moment of inertia m on which three forces may act: F_a, the force applied externally on the contact lens; F_m, the force exerted by the net added tension of the horizontal recti; and F_p, the net restraining force of all passive tissues in the orbit. The linear differential equation which describes eye movement θ in response to forces F_a externally applied or neural commands via active state tension F_o is shown in Figure D5. The bandwidth of the system in Figure D5 to a sinusoidally applied active state tension F_o is 1.1 cps at –3db. These data correspond to the empirical results when the question arises "What is the mechanical bandwidth or frequency response of the eyeball?"



Summation of forces: $m\frac{d^2\theta}{dt^2} + Fp = Fm + Fa$

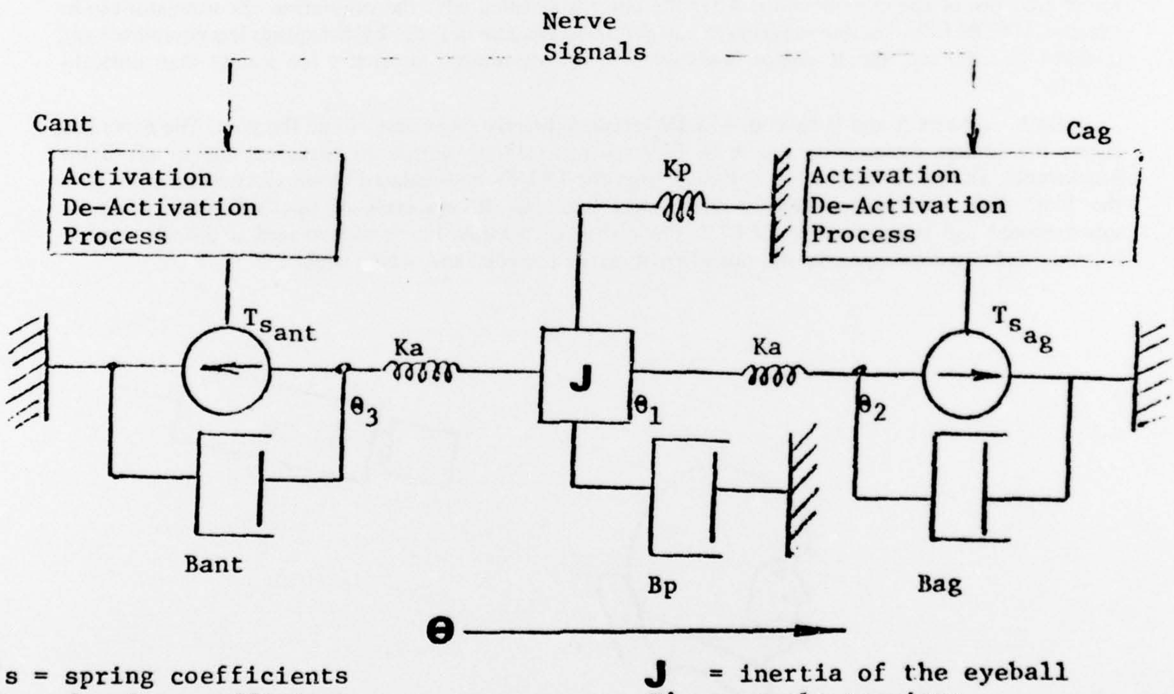
Fm's relationship to Fo: $\frac{Rm}{Ke}\frac{dFm}{dt} + Fm = Fo - Rm\frac{d\theta}{dt}$

Equation for Eye Movement: $R_1R_2\frac{d^2\theta}{dt^2} + (R_1K_2+R_2K_1)\frac{d\theta}{dt} + K_1K_2\theta = (K_1+K_2)Fp +$

$(R_1+R_2)\frac{dFp}{dt}$

Figure D5. **Robinson's model for the mechanical elements of the extraocular system.**

Cook (1967) presented a refined Robinson model of the human eye movement mechanism. Cook's objective was to cast the human eye-positioning mechanism into a realistic mathematical representation. The major problem with Robinson's model is that the available physiological data at that time were from animals, such as cats. Cook's basic approach was to assume the dynamic characteristics of the "plant" or muscle-eyeball combination based on available animal data. By measuring output position velocity and acceleration during eye movements, he was able to work backwards to determine what the control variables must have been in terms of nerve signals. Cook's model (see Figure D6) is similar to Robinson's except for two refinements. In his model, Cook considers the forces generated by the agonist and antagonist muscles independently, which accounts for the difference in characteristics of muscles when they are shortening (agonsit) and lengthening (antagonist). The other refinement is the addition of a nonlinear active damping term in the equation for the agonist and antagonist muscles. In Cook's model, the mass of the eyeball is shown as subject to forces from the antagonist and agonist muscles, as well as passive elastic and viscous forces. The major differences between Robinson's and Cook's models are in the viscous components, where Cook's passive damping coefficient is considerably lower than Robinson's element. Both models appear to account for the major characteristics of eye movement behavior; however, neither model has proprioceptive feedback of extra-ocular stretch.



k's = spring coefficients
B's = damping coefficients
C's = control signals

J = inertia of the eyeball
T's = muscle tensions
θ's = positions

Figure D6. **Cook's composite model for eye movement mechanism.**

The modeling actually performed by this investigator was to record frequency response data on a subject tracking a light spot moving sinusoidally along the horizontal axis. These data were Bode plotted and transfer functions were fitted to the amplitude and phase data. These second order transfer functions were then placed in a block diagram as potential "models" of the human's pursuit tracking system. It should be noted, here, that the anticipatory control term, or e^{Ts}, was not considered in the model. There is satisfactory experimental evidence that biological systems can anticipate or predict certain repetitive inputs before they actually occur (Milsum, 1966).

APPENDIX E: INTEGRATION OF THE NAC WITH THE ASPT

In the ASPT, most of the equipment required in the actual T-37 aircraft will not be necessary. Since there already is a video camera in each cockpit, only the helmet, reticle light, battery pack, fiber optics cable, and camera adapter are required. The low-light-level television (LLLTV), which is part of a closed-circuit TV system in the ASPT, will have to be either (a) relocated, or (b) moved forward, from its present position because the 39.4 inch fiber optics cable is not long enough to connect to the camera (see Figures F1 and F2). Since the NAC will become a part of the closed circuit system, no one will be required to calibrate the EMR (see Figure F2) other than the subject. Since the pilot's eye fixations can be monitored at the instructor/operator station (IOS) the experimenter, at that station, can direct calibration operations from his chair. If, during a maneuver, it is determined that the NAC is out of calibration, the ASPT can be put on FREEZE, the subject can be instructed to fixate on an object in the visual display or on the instrument panel. Using his left hand to turn the xy adjusters, the subject can make fine adjustments in the position of his eye-mark through voice contact with the IOS. The same procedure is true for adjusting the brightness with the image lens knob, changing the position of the eye lamp, or tilting the camera lens up or down. All of these adjustments can be made by the subject in the simulator under the verbal guidance of the experimenter. After the latter is satisfied with the calibration, the simulator can be released, UNFREEZE, and the experiment can continue. Because in it the EMR requires less equipment and is easier to calibrate, the simulator lends itself to eye movement research more readily than does the aircraft.

Both Cockpits A and B have an LLLTV installed directly above and behind the pilot. The zoom lens allows the camera operator at the A or B instructor/operator station to focus on any or all of the instruments. The zoom lens can be detached from the LLLTV and replaced by the fiber optics cable from the NAC. The 60° field of view of the camera lens and the eye-mark of pilot's fixation point are superimposed and transmitted to LLLTV; the combined presentation is then viewed at the advanced or conventional instructor operator stations where it can be recorded and played back.

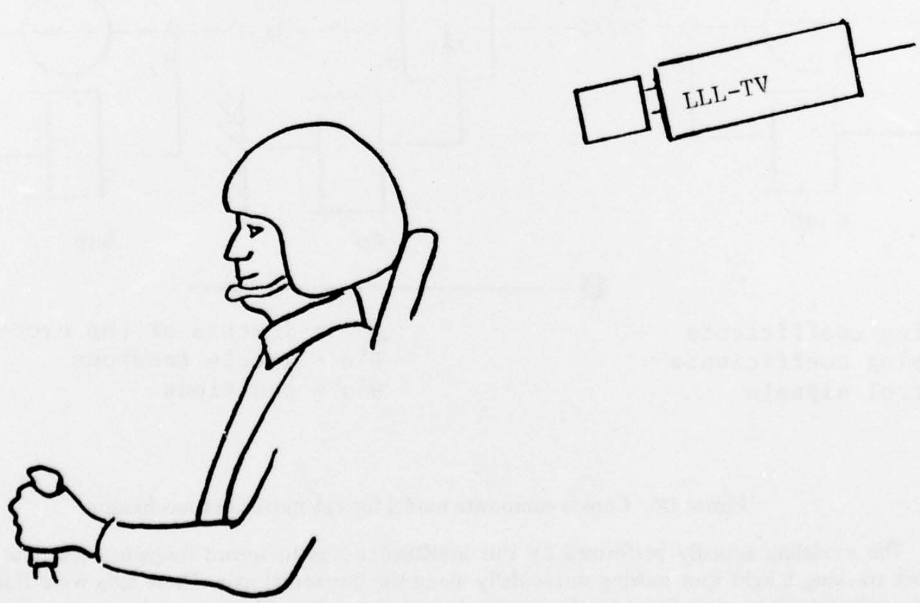


Figure E1. **ASPT with location of Low-Light-Level TV Camera.**

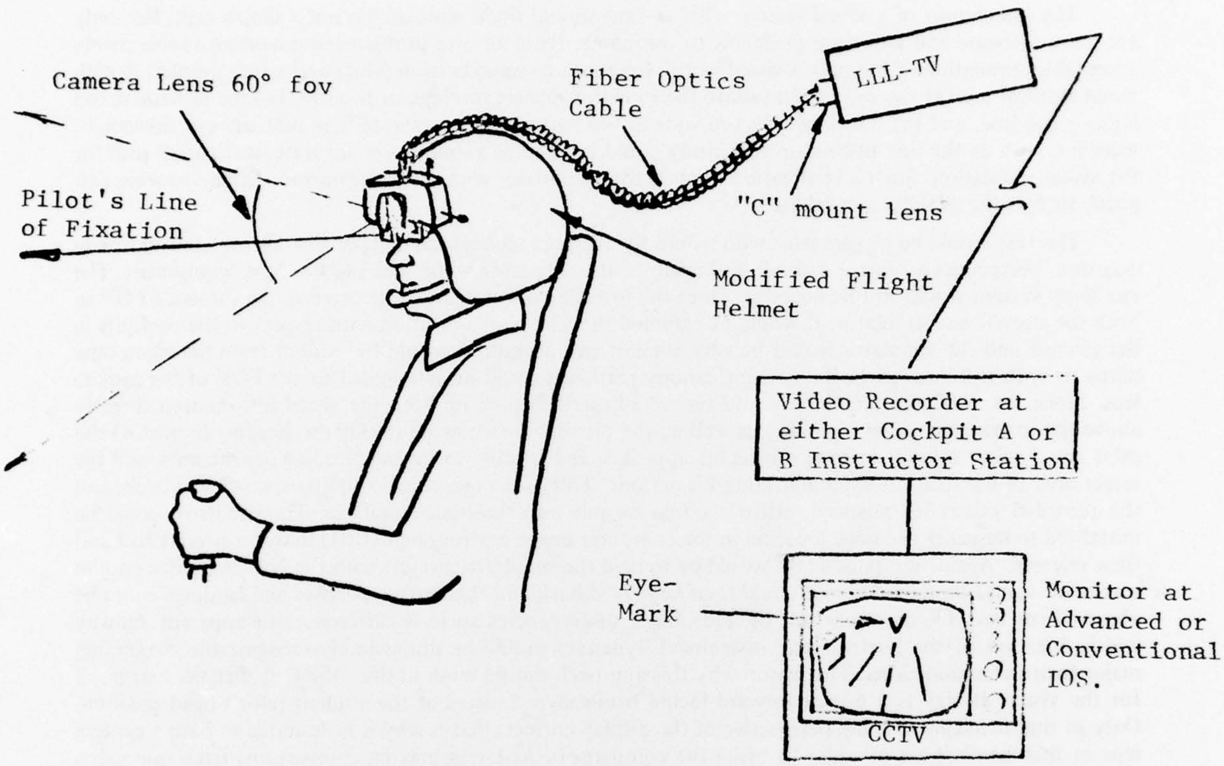


Figure E2. **ASPT with NAC Eye-Mark Recorder.**

OTHER USES FOR THE NAC EMR

Application of the NAC as a Verification Tool

Eye movements in the total FOV will be of material assistance in establishing the visual environment of the pilot and can be utilized in other programs. The data can be used directly by instructor pilots in directing the student's attention to particular areas of the visual field during training. Perhaps most important, the recordings and interviews will play an important part in establishing the optimal and image content for maneuvers recorded. Such information would be of vital interest in the ASPT visual data base as well as future UPT simulators. Direct comparison between visual environment of the pilot flying the aircraft and that of experimental configurations of the simulator will provide a baseline of data concerning the perceptual equivalence of the two systems. Canopy markings, however discrete, can be utilized in the aircraft and, thus recorded along with eye movements so that the eyes' line of regard can be referenced to both the aircraft and the simulator (visual display). This, too, is another method of verifying the simulator's visual data base; while on final approach at a certain airspeed, altitude, and rate of descent, the location of visual cues in the aircraft should directly correspond to the location of the same visual cues in the simulator. An occasional fixation on an object or two inside the aircraft or simulator, including the aural reference to the calibration check, would serve as a cross-reference to the mount in case the device slipped or moved during a maneuver.

Two applications of the NAC, other than recording eye movements for visual cue training, are verification of visual simulation and determination of the pilot's useful FOV.

Verification of Visual Simulation

The integration of a visual system with an operational flight simulator is not a simple task. Not only are there software and hardware problems to overcome, there are also problems in providing a subjectively acceptable simulation of the pilot's visual world. Common comments from pilots evaluating simulators with visual systems are (a) the eye-height (above the runway) appears too high or too low, (b) the horizon is too high or too low, and (c) the runway is too wide or too narrow. It is suggested here that an eye movement recorder, such as the one utilized in this study could be used as a simple, yet accurate, verfication tool for the visual simulation. Such a verification method for a simulator with a relative narrow display-viewing exit pupil, such as the ASPT, is presented.

The test would be by one pilot who would fly an approach and landing (or whatever maneuver was in question, perspectively) in the aircraft and again in the simulator while wearing the NAC equipment. The eye lamp system would not be necessary since the investigators would be interested in the camera's FOV in both the aircraft and simulator. It would be assumed that the pilot's position with respect to the cockpits in the aircraft and the simulator would be very similar; any deviations would be evident from the video tape taken in both instances since the cockpit/canopy markings could be referenced to the FOV of the camera lens. Since the NAC has a 60° FOV and can be adjusted to pick up both the visual information directly above the instrument panel (runway) as well as the primary instruments (altimeter, heading indicator) the pilot could select a point in time during his approach and landing to begin recording instruments, and the target area of his fixation while narrating his actions. This video recording could then be played back, and the recorded values for airspeed, altitude could be put into the basic simulator. The simulator could be initialized to basically the same location in the computer image environment (CIG) that the aircraft had and then released. Again, the pilot's task would be to land the simulated aircraft with the NAC recorder on; the maneuver would be recorded and could then be played back and the two approaches and landings could be observed on two TV monitors side-by-side. Major discrepancies such as differences in apparent runway width, location of the horizon, and instrument dynamics should be immediately recognizable, neglecting major instrument anomalies. The reason why this approach should work in the ASPT is that the exit pupil for the visual display is a 6-inch forward-facing hemisphere located at the student pilot's head position. Only in that hemisphere is the perspective of the display correct; that is why it is desirable to have a camera lens in that hemisphere in order to make the comparison. As far as making comparisons from one video tape to the other, instrument panel characteristics can be compared with respect to location from monitor to monitor. This same technique can be used for checking simulation of formation flying (does the simulated aircraft look too large or too small at a particular distance away), of taxiing, of instrument flight, of night flight. As well as for performance verification, the NAC can be used for modeling purposes. Refinements to the CIG data base can be made by comparing actual flights recorded on the NAC with simulated flights. Should there ever be a problem with verifying the location of the NAC with respect to the aircraft cockpit, markings could be placed on the canopy corresponding to the joints between windows in the visual display. This added reference would then add another degree of accuracy to the verification technique.

Verification of the Undergraduate Pilot's Useful Field of View

In order for the undergraduate pilot to perform the 8 basic maneuvers, an approximate FOV of +120°, −45° vertically and ±150° horizontally is required for visual simulation. This determination was not verified. As a result, it would be of interest to the Air Force and to future UPT simulator efforts to verify this FOV. The NAC is well-suited for such a task. This effort could be accomplished in the ASPT, since the geometry of the visual display (relative angles from the zero reference point to window joints, centers) is well established. The useful FOV could be established to within 1° of the actual, using this technique. If the NAC were used in the aircraft, the cockpit environment could serve as the reference for determining horizontal and vertical FOV.

Variable of Performance Measure in Motion/No-Motion Studies

Much controversy now surrounds the question of the utility of platform motion for flight training simulators. There exists very little data to support the training effectiveness of, for example, 6 degrees-of-freedom motion platforms for the Air Force's aircraft simulators. In structuring a matrix of experiments for attacking the motion/no-motion issue, a performance measure in the simulator and in the

aircraft, if it is a transfer of training experience, must be established. It is suggested here that a pilot's eye scanning patterns in the aircraft and the simulator would provide a useful variable in evaluating the utility of platform motion. For example, one question that could be answered by having a pilot wear an eye-recorder is: "During a simulated engine-out in the simulator, if the pilot receives an unexpected yaw cue, does the pilot react to this cue and how does he react to it?" This question is difficult to answer quantitatively by present techniques. It could provide researchers with data for evaluating the utility of platform motion. One would expect that if the motion platform gave the pilot the proper yaw cue, he would notice the problem and begin to scan his engine instruments. The eye recorder would give the researcher the data about how long it took the pilot to recognize the engine-out situation and what his scan pattern was after identifying the problem. Furthermore, if this experiment could be repeated in both the simulator and the aircraft, a relative measure between engine-out recognition in the aircraft and in the simulator could be established. Such a measure would provide hard data for deciding whether platform motion is of use in simulating engine-out maneuvers. Perhaps the best instrument to address such a study is the oculometer. The installation of an oculometer is discussed next.

NASA/Langley recorded pilots' eye movements in a 3-degrees-of-freedom simulator for the 737 airliner in both the motion and no-motion situations. The data have not been analyzed, but it is evident that the data are different from the motion to no-motion case. The pilots tended to fall into pilot induced oscillations in the no-motion landings; this is evident from the eye recordings. These preliminary results are early indications of the usefulness of recording eye movements in the simulator.

APPENDIX F: INTEGRATION OF AN OCULOMETER WITH THE ASPT – FUTURE CONSIDERATIONS

The ASPT CIG system can be described as a camera, mounted to an aircraft which is flying in one of a variety of environments (Basinger, 1973). A special purpose computer replaces the recording camera in the CIG system, and stores as numbers in the computer the optical edges making up the images of the objects in the simulated CIGs FOV. The ASPT environment is comprised of 100,000 total edges with the capability of processing up to 2,000 edges at one time, either shared between the two cockpits or dedicated to only one. The environment modeled has an area of coverage of 1,250 by 1,250 nautical miles with the data base consisting of a 500 by 500 nautical mile area and 100,000 edges. This data base includes Williams AFB, an auxiliary airport, all T-37 practice areas, and a T-37B lead aircraft. This represents an area of approximately 40 by 60 nautical miles. Beyond this area, a 50-nautical mile perimeter is also modeled to eliminate the appearance of the end of the modeled area. This data base will be sufficient for initial experiments to be conducted on the ASPT. However, this data base potentially can be expanded to 600,000 edges for future research (Basinger, 1973).

Since the CIG environment is comprised of an arranged sequence of numbers, the system readily lends itself to change. Objects can be added, deleted, or modified easily. As a result, the CIG system's visual display, and thus, the ASPT, lend themselves to modification and are at the whim of the researcher. This built-in versatility is what makes the ASPT visual display system a primary candidate for eye movement research. With the CIG approach, different visual simulation configurations can be obtained quickly. Several data bases are stored on the CIG computer's disc memory, any of which can be used. To change the FOV, a data change is made in the software to give a different display specification. The repeatability of the visual simualtion performance is insured by the CIG approach since all processing is digital (Basinger, 1973).

The Human Factor Branch at NASA-Langley has been actively using an oculometer as a research tool during quantitative measurements of performance by different pilots conducting instrument approaches. NASA uses the device to determine how the panel and approach path are scanned by the expert performer as compared to others (Waller, & Wise, 1975). Preliminary studies of pilots' eye movements during simulated approaches have already produced some significant data on where and how pilots scan and where their eyes spend a major portion of the time. NASA researchers have determined that eye movements have a high correlation with pilot workload and recommend the device for training pilots and evaluating the quality of one visual display or another. NASA suggests that if the oculometer helps to determine what cues the expert performers (pilots) use, the data may help in training fledgling pilots. NASA-Langley has reduced the oculometer in size in order to integrate the system with a simulator's instrument panel.

NASA studies substantiate pilots' strategies in flying in the instrument mode with an without automatic control. Seven experienced Piedmont Airlines pilots flew instrument approaches in a 737 simulator equipped with an oculometer. They flew approaches in both the manual mode (in which they had to control the aircraft) and the coupled mode (in which the aircraft control is coupled to the ILS). NASA researchers documented the different strategies the pilots assumed when flying under manual or controlled modes. They found that the pilot flying ILS in the manual mode spent an average of 72% of his time fixating on the flight director, which is an attitude directional indicator with command bars. Eight percent of his time in the manual mode was spent on the airspeed indicator. His mean dwell time on the flight director was 1.6 seconds in the manual mode. However, a drastic change in strategy was noted when the pilots landed the simulator in the coupled ILS mode. The averaged only 50% of their time fixating on the flight director and 22% of their time on the airspeed indicator with a 0.8 second mean dwell time on the fligh director. What do these data indicate?

The data tend to show two different strategies for the two different ILS control modes. Although standard performance data would show no significant difference from one mode to the other, the oculometer data indicate that the pilots are performing differently in the two tasks. During the manual mode, the pilot appears to be flying with an integrated picture in his mind of where he is now and where he is going. In the coupled mode, however, the pilot is no longer a "stick jockey" but rather a monitor; he doesn't have to fly the aircraft, just monitor its progress. The oculometer captures this change of strategy in

his eye movement scan pattern. Studies such as these that NASA is performing are providing insight not only into strategies that pilots can and do assume, bust also which designs of flight directors appear to give the pilot maximum information in the least amount of dwell time. NASA researchers intend to use the oculometer to conduct further display experiments in the future. The effect of turbulence on the 737 pilots' data was negligible.

With the combination of a versatile visual display and an established eye movement measuring device, the oculometer, the field of pilot eye movement research is wide-open at AFHRL/FT. What is intended in this section of the report is to (a) describe how an oculometer could be integrated with the ASPT, and (b) suggest avenues of research in eye movement control and recording.

Figure G1 depicts a theoretical integration of an oculometer with the ASPT. The oculometer's optical head, reduced in size so that it can replace an instrument dial on the student's or (preferably) instructor's side, is shown in cockpit A. An instructor pilot, or expert performer, is "flying" cockpit A on an approach and landing. The oculometer is tracking and processing his eye movements. The mirror control and sensor unit are installed in the simulator's instrument panel, the signal processor (mini-computer) is located off-platform; cabling is required between the sensor unit and the mini-computer. The mini-computer transforms the eye movements into values of eye direction and pupil diameter, which not only tell the investigator what the pilot is looking at but also what his reaction is to it. These values are then converted into analog signals which can be recorded on an x-y plotter, used to annotate a TV picture, or control the CIG system in one fashion or another. This control aspect of the oculometer will be discussed later.

The other application of this analog signal out of the mini-computer is as an input to the CIG system as a location of the pilot's fixation point. In other words, once the signal processor has determined the pilot's eye direction and pupil diameter, the values for eye direction can be recomputed in the mini-computer and converted to appropriate numbers for the CIG system. Since the CIG system has a number of point lights generated, and since a point light would lend itself to an approximation of a pilot's fixation point, the calibrated eye direction values could be directly inputted to the special purpose computer's point light generator. The locations of these point lights are updated 30 times per second with respect to latitude and longitude. One of the point lights, computed at its smallest size (2 by 2 elements), could be designated as the receiver of the oculometer's eye direction data. Thirty times per second, eye direction data could inputted into the special purpose computer corresponding to an x and y in the CIG raster plane. (By going directly into the special purpose computer with the eye direction data, the general purpose computer program is avoided. Processing the eye direction information through the general purpose computer would impair the operation of the CIG's real-time program by increasing its size and add an additional 33 1/3 milliseconds delay to the presentation of the eye direction because of the additional processing time.) Approximately 50 milliseconds after the mini-computer placed the appropriate value for x and y in the special purpose computer, the eye location would be displayed in cockpit B.

Once projected in visual display B, the novice pilot, who is "slaved" to the expert performer in cockpit A in that the visual, G-seat, motion, stick, and pedal dynamics of cockpit A are being duplicated by cockpit B, cannot only "feel" the performance of his instructor in A, but also see what his instructor uses for visual cues in performing the required basic maneuvers. Likewise, this system can work in reverse. The student can be placed in cockpit A, with the oculometer, and have cockpit B slaved to A with his instructor in B. In B, the expert performer can observe his understudy's eye movements and perhaps detect anomalies in the student's scanning pattern and perception of helpful visual cues. Another option is to record the student's flight, including eye movements, and play it back to him.

This is only one application of the oculometer to the ASPT CIG system. Another application is the use of the device to control the CIG system (note the broken lines in Figure G1). Since a pilot's eye direction is constantly monitored by the oculometer, and since the device can output analog signals, it would be desirable to use this information in controlling the CIG environment. One example would be to develop an advanced data base which could be controlled by the pilot's fixation point. In other words, if a pilot were "landing" the simulator and his region of fixation was on the runway and the environment immediately surrounding the runway, the environment outside this envelope could be immediately, and dynamically, reduced in detail in real-time. This reduction in the amount of objects and detail in the pilot's periphery would allow more edges to be available for processing in the area of interest which would give the region of fixation more detail with more visual cues. This would be a "poor man's" way of increasing the

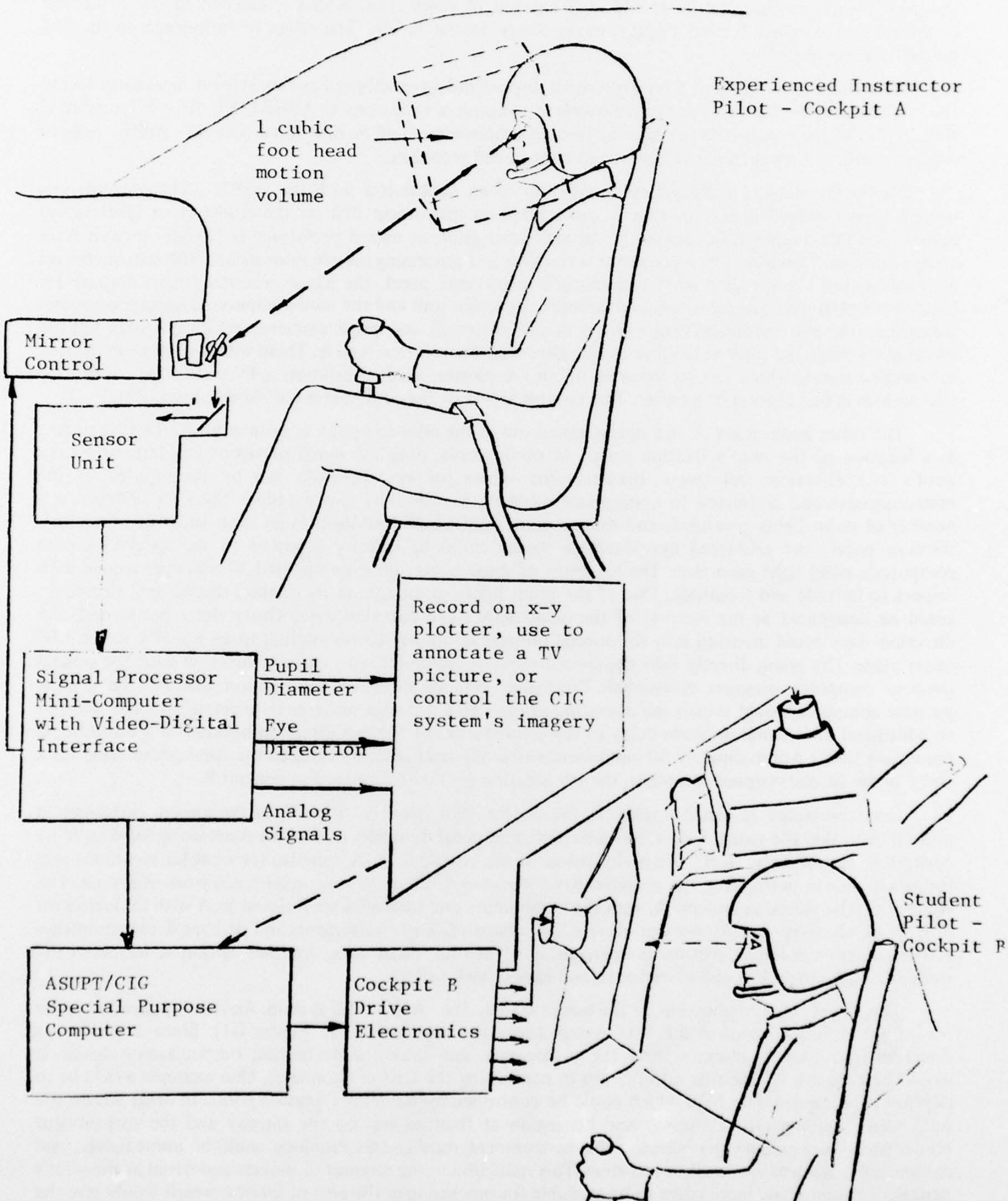


Figure F1. **ASPT/oculometer interface.**

edge capacity of the CIG system without adding additional computation equipment. Likewise, a data base could be generated with the intent of permitting only ±30° (for example) about the pilot's line of regard to be processed with maximum detail, and that region outside ±30°, with minimum detail. Such experiments or applications of the oculometer to control the visual display are possible.

On disadvantage the oculometer has compared to the NAC is the capability of readily displaying eye fixations alternately on the instrument panel and visual display. Since the eye movements are referenced by a moving point light in the CIG system, there is no CIG related method for indicating which instrument the subject is scanning when his eyes are off the display. This could be accomplished by using the oculometer's analog output as a calibrated input to the basic simulator computer. Theoretically, the instrument being scanned could be brightened in intesity by appropriate commands from the basic simulator computer. This variable intensity feature is not present in the system now, but could be added along with the appropriate software module in the real-time program.

Another approach to monitoring pilots' eye movements with the oculometer without interfacing the device with the CIG system would be to superimpose the eye position on a TV picture of the instrument panel and visual display. This could be accomplished by remounting the LLLTV in cockpit A to a position near the pilot's head such that: (a) The camera lens could pick up at least a 60° FOV including the student's instrument panel and the forward looking channel (number 1) in the display. (Parts of channels 2, 4, and 5 (left and right of the forward-looking channel) could possibly be monitored as well, depending upon the type of camera lens. The eye directions calculated in the mini-computer could then be related to the reference point of the LLLTV camera.) (b) The camera should be located in or near the visual display's exit pupil so that distortions, aberrations, and focusing problems are minimized. Unfortunately, the ideal position for the oculometer's camera lens is at the pilot's eye position, since the display is collimated to that point. This is where the NAC has an advantage over the oculometer, since its camera lens is mounted directly above the eyes on the flight helmet. Using the oculometer with the LLLTV, recordings could be made and analyzed.

Future Opportunities in Eye Movement Research

Projecting or recording one pilot's eye locations from one ASUPT cockpit into another is only one avenue of research for AFHRL/FT. With the CIG system and its flexibility, hundreds of other research adventures are available for AFHRL/FT to pursue. These include but are not limited to the following:

1. The study of pertinent and non-pertinent visual cues around a runway.
2. Image content necessary in a visual scene to successfully complete a mission.
3. T-37B instrument panel layout research.
4. Study of the effects of optical illusions in the flight environment.
5. Correlation of pilot's eye movements and pilot's performance.
6. Study of the effects on pilot's performance of highlighted visual cues.
7. Eye movements in the aircraft and ASPT and their similarities or perceptual equivalence.
8. Evaluation of scan patterns to develop a model of pilot workload in order to replace subjective pilot ratings.

☆U.S. GOVERNMENT PRINTING OFFICE: 1978-771-122/20